FOURTH WINDSOR WORKSHOP

ON

ALTERNATIVE FUELS

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ON
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SUMMARY

The Proceedings of the Fourth Windsor Workshop on Alternative Fuels has been compiled as a record of the latest developments, trends and activities in the steady progression of various alternative fuel stratiges.

Once again this year the atmosphere at the Workshop was held at a very informal level in order to stimulate and encourage open discussion, even if this approach requires a sacrifice of the completeness and thoroughness of the proceedings.

We wish to thank all those people who took part in the Fourth Workshop and helped to make it such a sucess.

We look forward to next year.

FOURTH WINDSOR WORKSHOP ON ALTERNATIVE FUELS

June 20 - 22, 1988

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" A REVIEW OF THE EFFECTS OF FUTURE CANADIAN DISTILLATE FUELS ON HIGH/MEDIUM SPEED DIESELS "

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ABSTRACT

Canada has been involved in an ongoing research program to determine the effects of future diesel fuels on the performance, combustion and durabilty characteristics for high and medium speed diesels. This paper discusses the recent past and present fuel situation in relation to the fuels used in the experimental programs. An ensemble summary of the results of studies on seven diesel engine families are presented. Attention has been focussed on the fuels related effects of combustion pressure rise on engine durability for medium and high speed diesels. Newly acquired results are presented that describe the durability degradation of a Detroit Diesel 6V92TA high speed diesel engine using low ignition quality fuels. Advances in pilot injection for reducing rates of combustion pressure rise are discussed for a Detroit Diesel 6V53T engine. Medium speed diesel durabilty with residual fuel blends is summarized along with the development of ceramicized exhaust valves for the extension of valve life with these and conventional fuels. Recommendations for further investigation are posed in the context of fuels related durability, cold starting characteristics and emission requirements.

INTRODUCTION

During the 1970's, fuel shortages led to increased research to determine the minimium fuel requirements for diesel engines. This research focussed primarily on relating the effects of reducing fuel ignition quality (cetane number) to engine operational, performance and combustion characteristics. The concept of lowering diesel fuel cetane level was based on the premise that an increased supply of lower cost middle distillates would result. The cost reduction was based on less hydrogen being needed during fuel refining processes. In Canada this concept looked particularly attractive due to the abundance of tar sands reserves and the extensive hydro-treatment employed in bitumen upgrading. Fuel cost increases due to middle east supply uncertainty and the likelihood of future increases to tar sands processing capacity in Canada were major factors in the initiation of a number of fuels related diesel engine studies. These studies involved engine test programs where a number of experimental fuels were blended to represent the Canadian future fuel scenario. The experimental fuels contained varying percentages of tar sands derived components, light cycle oils, components derived from conventional sources and in some cases residual fuels.

PRESENTED/PROJECTED CANADIAN DIESEL FUEL PERSPECTIVE

The Canadian diesel fuel market demand continues to steadily increase. This increase in recent years has been slowed due to the conversion to natural gas from home heating fuels. This has released some middle distillates for the diesel pool. Since a major portion of the heating oil is cracked gas oil of low ignition quality (cetane number 15-30), there are limits to the amount of this material that can be added. Presently,the diesel pool in central/western Canada has about 10% of its components derived from the tar sands. In the future this percentage is expected to increase across Canada as the supply of of conventional crudes diminish and the market prices increase. It is anticipated that higher market prices will make the cost of tar sands fuel production more economically attractive. Synthetic diesel fuel has been described [1]+ as having high levels of aromatic components (the aromatic structures are mostly of the single ring benzoid type with a great many side-chain substituents on each ring). Synthetic diesel fuel has a low sulphur content which is thought to be beneficial for minimizing particulate formation during the diesel combustion process. Additionally, its cloud and pour points are depressed due to the low wax content. This enhances its capability at low temperatures. These properties and others as described in [1] are compared in Table 1* to diesel fuels derived from conventional crude sources. The recently deployed Shell Scotford refinery is now processing Syncrude and Suncor synthetic crudes to a diesel fuel cetane level closer to the Canadian General Standards Board minimum of 40. It is expected that future refineries for synthetic crudes will have similar capability. However, economic benefits may be realized if this current CGSB minimum could be further relaxed. As such one of the prime objectives of Canadian fuels/diesel research activity has been to determine if there are real impediments to further lowering the minimum cetane number. Some conceivable impediments are: engine performance/operabilty degradation, increased combustion chamber deposits, increased gaseous/particulate emissions, reduced cold starting capability, decreased fuel efficiency and reduced durability. In the following sections, this ensemble progress will be reviewed.

[+] Numbers in parentheses designate references at the end of the paper.

* Tables and figures are at the end of the paper.

FUEL/DIESEL RESEARCH SUMMARY

EXPERIMENTAL FUELS

The Canadian research coordinated by the Federal Panel on energy R & D has been carried out in laboratory/field environments by universities, private industry and provincial/federal departments. A wide cross section of engines have been studied and are listed in Table 2. This table describes the engine, program test facility and lists the most recent relevant references [2,13] from which this information was taken.

This summary paper has considered all of this information but will primarily concentrate on the engines in each of the research programs that have commonality of test fuels. The studies with common test fuels have been identified with asterisks beside the engine model number in Table 2. Table 3 contains a rationale for selection and a source description of the test fuels in the fuel specification/compositional analysis Tables (4-8). Tables 4-6 contain the residual fuels analysis data; however, they also provide an indication of the diversity of the fuel matrices used in the studies being considered. Tables 4-6 are for the Bombardier B-251 engine [3]. Tables 7-8 are for the Deutz F1L511D engine [4]. It should be noted that Fuel A in Tables 4-6 is a commercial diesel fuel selected to replicate the high stability diesel reference fuel, Fuel A in Tables 7-8. The Fuel C in Tables 4-6 was a different blend batch from the Fuel B in Tables 7-8; this accounts for some small differences in values listed for each fuel. This common test fuel concept (Fuels B and C) was initiated by the Canadian General Standards Board (CGSB) in 1978. The test fuel has been referred to as the 1990's and beyond experimental fuel. Current thinking suggests that the amount of tarsands derived diesel fuel in the domestic pool will not reach 39 % (the amount in the 1990's fuel) until the early 2000's. Hence, this 1990's and beyond experimental fuel can be thought of as a worst case fuel in the 1990's, but still, very relevant for experimental purposes to exaggerate the more subtle fuel quality relaxation that is likely to occur.

From Tables 4-8, a general comparison of properties (ref. fuel vs the 1990's) has been tabulated in Table 9. The most significant property variations are the increases in total aromatic content and the increased viscosity. The increased aromatics content, as described by three different fuel analysis methods/techniques, is directly related to the increased viscosity/density and the decreased hydrogen content of the fuels. During the early years of these research efforts there was little consensus for characterizing the aromatic nature of the test fuels. Recent studies [14] have shown promise in extending the proton NMR to provide more detailed fuel structural information on a average molecular basis.

Diesel Engine Experiments

High and medium speed diesels tested with the reference fuel and the 1990's fuel will be discussed together for this summary in terms of their performance/combustion-emission behaviour. The durability results for the residual fuel blends with the Bombardier B-251 medium speed diesel will be treated separately. Each of these studies will be referred to by the engine used in the experimental program as listed in Table 2. A final section will discuss the low temperature capabilities of four diesel families with a matrix of fuels that include conventional and tarsands derived components. It should also be mentioned that all of the engines in Table 2 employ some form of direct fuel injection system.

An analysis of the engine/fuel experiments with summary tables is used to describe experimental parameter variation of the test engines relative to the reference fuel. Discussion will focus on the experimental observations where significant differences were found between the 1990's fuel and the reference fuel. Recommendations are made for future experiments in light of these findings.

Engine Experiment Analysis

For the DDC 6V92TA engine experiments [7,8] the performance/combustion-emissions/durability data is summarized in Table 10 for maximum speed and load conditions. The maximum output power conditions were chosen for their comparative commonality with other engines and for demonstration purposes. Similarly, Tables 11-13 have been made for the DDC 6V53T [6,13] for the Cummins NTC-400 [11] and for the only medium speed diesel the Bombardier B-251 [3,12]. From these summary tables substantial increases are indicated for ignition delay, rates of combustion pressure rise, Bosch smoke number, CO, NO_x, total particulates, bearing wear and top piston (fire) ring wear. The observed Bosch smoke number increases occurred in low level measurements and this, in combination with the inherent inaccuracy of the technique, may have distorted/obscured the exact magnitude of the increases. In general, for most of the engines there appeared to be an increase in the Bosch smoke numbers at high speed and load conditions. For the NTC-400 this increase was found over most of the engine operating range, consistent with the increased total particulate levels for that engine.

The magnitude of the Bosch smoke number increases seem to be engine dependent. Similar statements can be made for CO emissions where there appeared to be a slight increase for most engines with the 1990's fuel. Any substantial increases or decreases seemed to be engine dependent and confined to a particular area of the engine speed/load operating range. An examination of other speed/load conditions for the diesel engines using the 1990's fuel indicate similar findings. In summary, the use of the 1990's fuel had little effect on:

- Engine/Vehicle Operability
- Fuel Comsumption
- Output Power
- Peak Cylinder Pressure (Turbocharged) - Unburned Hydro Carbons
- Carbon Monoxide
- Deposits (Combustion Chamber/Exhaust System)
- Cold Starting

However, the utilization of the 1990's fuel caused increases to:

- Ignition Delay
- Rates of Combustion Pressure rise
- Top Ring wear on Pistons (DDC 6V92TA)*
- Slipper Bearing Wear (DDC 6V92TA)
- Total Particulate Emission (CUMMINS NTC 400) and Bosch Smoke number
- Nitrogen Oxide Emissions
- Cold Idle Roughness
- White Smoke Production
- Peak Cylinder Pressure - naturally aspirated

The following discussion will treat each of these areas separately and attempt to identify the fuel/combustion related reasons for these increases.

Ignition Delay

The increased aromatic content (increased mono-aromatics, increased di-aromatics and increased poly ring aromatics) and decreased paraffinic content in Tables 4-8 for the 1990's fuel, relative to the reference fuel, has led to longer ignition delay periods after the start of fuel injection. The essential cause for this is associated with the increased proportions of condensed ring components in the 1990's fuel. These condensed ring fuel components require higher energy levels (combustion pressures and temperatures) before preflame reactions permit sustained combustion to occur. High initial rates of fuel injection also increase the time necessary for preflame reactions to be completed, because the heating time requirement for a large charge of fuel is greater than for a small charge. The increased ignition delay with high rates of initial fuel injection lead to a higher percentage of premixed combustion and a decrease in the amount of diffusion combustion.

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* - observations are based on tests for one engine family, as indicated within the brackets.

Another controlling factor for ignition delay time is the combustion chamber temperature-pressure at the time of injection. Ignition delay time can be substantially reduced by injecting at a retarded injection timing, which has the effect of increasing the combustion chamber pressure/temperatures at the initiation of injection [8].

The longer ignition delay time for the 1990's fuel would also be contributed to by the higher fuel viscosity which tends to impede the fuel preparation process through poorer atomization. This process would be somewhat offset by increased injection pressures as a result of the higher density of the 1990's fuel. Higher fuel injection pressures tend to promote improved fuel/air mixing due to greater injection spray penetration and associated increase in turbulent mixing. In general increased ignition delay tends to increase rates of combustion pressure rise. The rates of combustion pressure rise have been found to contribute significantly to diesel noise levels [6]. As such, a concern for potential deleterious effects to engine durability has been expressed in this study.

Rates of Combustion Pressure Rise

For the DDC 6V92TA [8] twenty-one 6.25 hour durability tests were undertaken to assess the effect of fuel cetane number variation* and fuel injection characteristics on excessive top piston (fire) ring wear [7]. It was initially postulated that the increased top ring wear, determined from 500 hour durability tests using the 1990's fuel [7] was due to elevated average rates of combustion pressure rise. It was found from the 6.25 hour durability tests that the weight loss of chromium plating from the top or fire ring, as shown in Table 14, was significantly affected by fuel injection timing, fuel cetane level (aromatic content) and fuel injector type. This weight loss from the fire rings was determined by analysis of chromium content in the lubricating oil. Within the experimental error for combustion pressure rate determinations, fire ring wear was found to increase with decreasing fuel cetane level and to increase with advanced injection timing. In both these cases the fire ring wear can be observed to correlate to the increased rates of combustion pressure rise. However, the rates of wear for the retarded injection timing were as high or higher than the rates for advanced conditions. An examination of the combustion pressure-crank angle diagrams for the Deutz single cylinder engine [4], an example of which is shown in Figure 1, illustrates how fuel injection timing increases rates of combustion pressure rise, peak combustion pressures and how it affects the amplitude of the high frequency pressure oscillations superimposed on the combustion pressure signal. Further analysis of the DDC 6V92TA combustion pressure diagrams, in Figure 2, revealed that the vibrational amplitude increased as the fuel cetane level decreased and the vibrational amplitude decreased as the fuel injection timing was retarded relative to the base timing. However, the magnitude decrease for the retarded timing relative to the advanced timing appeared to be small. For the retarded timing conditions it was noticed that the highest amplitude portion of combustion pressure oscillations seemed to consistently occur as the piston went through top dead centre. This led to the suggestion that the increased ring wear may be a function of gross rates of combustion pressure rise, which in turn seems to have a direct correlation with the the amplitude of the combustion pressure oscillations. The second suggestion is that the location of the pressure oscillations relative to top dead centre appears to influence the fire ring wear for the retarded timing condition. This latter suggestion may be due to vibrational movement/flutter of the top rings or the piston or a combination of both. The suggestion that the whole piston may also be vibrating seems quite plausible in that the wrist pin slipper bearings were found to have higher wear than other bearing surfaces during the 500 hour durability tests [7]. Further experimentation is required to validate this suggestion.

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* The two test fuel blend components for the two test fuels (cetane numbers 34.5, 30.0) were the same two used for the 1990's fuel.

A different approach for combustion pressure rate reduction was undertaken for the DDC 6V53T [6,13]. Three types of engine modifications to reduce rates of combustion pressure rise were considered: air box heating, tuned injection and optimized dual injection or pilot injection. Tuned injection was defined as the control of the electronic fuel injection signal to best fit the indicated and combustion parameter data recorded with that of a mechanical injector. Air box heating was found to be ineffective and tuned injection produced only marginal benefits.

The optimized electronically controlled dual fuel injection (also commonly called pilot injection) was shown to have the capability to significantly reduce rates of combustion pressure rise. The rates of pressure rise were decreased to lower values on this engine than with the reference fuel. The values for the reference fuel were determined with six conventional mechanical injectors. This dual injection concept was performed on one of the six cylinders while the remaining five cylinders were fueled with mechanical unit injectors. As a result only indicated parameters could be obtained for the cylinder employing dual injection. Indicated performance was improved in terms of power and thermal efficency. This study suggests a potential exists for substantially improved combustion through advanced fuel injection techniques.

Emmisions (Particulate and Oxides of Nitrogen)

A performance/combustion-emissions study on the Cummins NTC-400 [11] has generated the only particulate measurement data for the 1990's fuel. The acceptibility of the 1990's fuel from a particulates stand point was found to be problematic. The levels of total particulates for the 1990's fuel (Fuel B), in Figure 3 can be seen to be 20 % higher than the reference fuel (Fuel A) over the engine operational map. It was concluded that higher aromatic content and sulphur levels were responsible. There is evidence to suggest the effect of sulphur is the major contributor. For the CAT 3406 engine/fuel tests [9] the fuel matrix included a test fuel (E) that had 71% by volume of its blend components derived from synthetic origin. This fuel when compared to the reference fuel had a lower sulphur level (.117 vs .229), higher 90% distillation temperature (325 vs 296°C), higher aromatics level (46.4 vs 33.6%) and the same percentage of cracked gas oils 5%. The reference fuel produced higher smoke opacity and unburned hydrocarbons across the engine operating range. This suggests that the reference fuel produced greater smoke and hydrocarbons due to higher sulphur levels. Presently, in both Canada and the United States, major studies are being carried out to determine the role of fuel aromatic and sulphur compounds in diesel engine particulate formation. Understanding the role of aromatic compounds is particularly important to Canada with the extensive supplies of western tarsands deposits which yields a highly aromatic diesel fuel but, as mentioned earlier, low in sulphur.

The solvent extractable particulates shown in Figure 4 indicate less substantial changes relative to the reference fuel. The largest increases occurred at low load conditions over the speed range. In summary, impending particulate legislation in the US and possibly Canada suggest increased effort be given to the role of diesel particulate formation. In this work the contribution of lubricating oil should not be neglected as it has been found to be substantial contributor [15] to particulate formation.

The impending US legislation for particulates and oxides of nitrogen (NO_x) is summarized in Figure 5. In this graph, the trade-off between NO_x and particulate emissions for production and development engines is also shown. An engine modification to improve NO_x usually increases particulates and vice versa. Besides the NO_x particulate trade-off there is a NO_x-hydrocarbon (HC) trade-off and a NO_x - brake specific fuel consumption (BSFC) trade-off. Legislation is also impending to restrict HC emissions levels to 1.3 g/bhph in 1991 and 1994. The US Environmental Protection Agency (EPA) is also considering legislation to limit fuel sulphur and aromatics levels to 0.05 % mass and 25 % by volume respectively.

In general terms, the engine constraints to the above mentioned trade-offs are: 1) Increased combustion pressures and temperatures usually lead to increased NO_x, 2) Increased rates of combustion pressure rise lead to increased NO_x, and 3) Improvements to air/fuel mixing lead to increased NO_x. It should be noted that these trade-offs and associated constraints have been largely determined with conventional injection equipment. There is some evidence in the work done for development engines [16,17] that control of start of injection and subsequent rate of injection leads to wholesale improvements to particulates, NO_x and HC levels. This suggests that more fundamental information is required to determine how NO_x/particulate variation behaves over the premixed/diffusion combustion period for advanced injection techniques.

For all of the engines tested with the 1990's fuel or other low cetane fuels the NO_x levels tended to increase to about 20 % higher levels for fuels down to a 34 or 35 cetane number level. Reductions to rates of pressure rise through improved start of injection and injection rate control may lead to a substantial improvement for both NO_x and total particulates. It is suggested that these research areas could yield a high payoff in terms of future diesel development.

Low Temperature Capability of Diesels using Low Cetane Fuels

In this low temperature study [9], six test fuels were blended to permit fuel variations in natural cetane, chemically enhanced cetane number (ignition improver), back-end volatility (variation of $T^{9}{}_{0}$) and synthetic vs. conventional crude sources. As is indicated in Table 2, one engine, the CAT 3406 was tested in a laboratory setting while the remaining engines were tested in trucks. For the CAT 3406, it was found on the test stand, that increasing fuel cetane, either naturally or with ignition improver, slightly improved cold startability while reducing white smoke production. Idling was smoother with higher cetane fuels. For an engine at operational temperatures, lower cetane fuels showed no increase in black smoke, hydrocarbon and carbon monoxide emissions. Nitrogen oxide emissions and rates of combustion pressure rise were reduced with increased fuel cetane number. An increase to the 90 % distillation temperature (T_{90}) showed no effect on startability or ignition delay. However, white smoke production increased. For the engine at operational temperature, increased T_{90} showed no changes to black smoke and oxides of nitrogen. Hydrocarbon emissions were reduced and carbon monoxide emissions increased slightly.

Comparison of a conventional fuel to a fuel containing substantial amounts of synthetic components [9] showed slight decreases to nitrogen oxide emissions for the synthetic fuel. No correlation between fuel properties and engine performance in terms of cold starting emissions or fuel economy was apparent for the six fuels studied.

It was found for the truck low temperature starting driveability experiments that engine design had the greatest influence on startability, cold idle roughness, white smoke production and driveability. Fuel quality effects on startability were minor while the effects on white smoke production were substantial (in particular the T_{90} and natural cetane number). Cetane improver was not as effective as natural cetane in decreasing white smoke production. The synthetic fuel did not produce more smoke relative to the fuels from conventional crude sources. Fuel effects on driveability were only significant on one truck with the Cummins NTC-400 operating at -25°C or lower. Higher fuel viscosity substantially worsened driveability.

Medium Speed Durability using Residual Fuels

For these tests with the Bombardier B-251 medium speed diesel, a commercial diesel fuel was blended with 30% by volume residual fuel [12]. The fuel analysis is tabulated in Table 6. The vanadium content of 83 ppm and sodium content of 30 ppm was responsible for premature exhaust valve failure. For the durability test a two hour test cycle consisted of 75 minutes at 1100 rpm/2250 bhp, 15 minutes at 800 rpm/1154 bhp and 30 minutes 300rpm/no load. For the residual fuel blends, 12 Inconel exhaust valves with mechanical clutch rotators were used in addition to 12 of the conventional design 21-4N Austenitic steel exhaust valves. All 24 exhaust valves employed Stellite-6 seats.

During the 500 hour durability test operability difficulties were encountered. The test had to be stopped at the 442 hour point due to severely guttered exhaust valves (21-4N Valves). One of these valves is shown in Figure 6. Subsequent laboratory failure analysis indicated this valve failed due to the corrosive attack of fuel bound vanadium/sodium.

Apart from the valve failure, the other essential comparative differences between the results for the residual fuel blend (fuel G) and 1990's fuel (fuel C) during the 500 hour tests were: more extensive fuel injector/fire deck deposits, slight lacquering of the piston skirts, a thin layer of brownish-yellow deposits in the exhaust manifold and very slight alkalinity depletion (TBN) of the lubricating oil.

In an effort to improve the durability life of medium speed exhaust valves with conventional fuels and residual fuel blends, NRC has designed a ceramic wafer insert to be used in the seat face of metal valves. It is thought that the wear capabilities and inertness to corrosive attack of the ceramic material would be beneficial relative to metals presently used. The first prototype, shown in Figure 7, has recently undergone survivability tests and logged 74 engine test hours at engine conditions up to maximum speed/load.

CONCLUSIONS

Summarizing the results from studies on a variety of medium and high speed diesels [2-13] the following conclusions have been reached.

1. For the diesel engines indicated in Table 2, use of the 1990's fuel with higher aromatic content (mono, di and poly-aromatics) (Table 5 and 8) has resulted in only minor changes to :

- Engine/Vehicle Operability
- Fuel Consumption
- Output Power
- Peak Cylinder Pressure (TC)
- Unburned Hydro Carbons
- Carbon Monoxide
- Deposits (combustion chamber and exhaust)
- Cold Starting

2. For the diesel engines indicated in Table 2, use of the 1990's fuel with higher aromatic content (mono, di and poly-aromatics) (Table 5 and 8) has resulted in significant increases to :

- Ignition Delay
- rates of combustion pressure rise
  - Top ring wear (DDC 6V92TA)* - Slipper Bearing Wear (6V92TA)
- peak Cylinder Pressures. NA+
- Total Particulate Emissions (CUMMINS NTC-400)
- Nitrogen Oxide Emissions
- Low temperature:idle roughness
  white smoke

3. For the DDC 6V53T diesel with the 1990's fuel dual or pilot fuel injection decreased rates of combustion pressure rise to values lower than those with the reference fuel employing standard fuel injectors.

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* ( ) Brackets indicate conclusions are based on tests for one engine family.

+ NA - Naturally aspirated engines

4. Top ring wear on the DDC 6V92TA appeared to correlate to rates of combustion pressure rise for advanced and reference injection timing. Increased wear for the retarded injection did not correlate with rates of combustion pressure rise. The location of high frequency oscillations near top dead centre appeared to influence the observed increases to top ring wear.

RECOMMENDATIONS

1. Further study is required to determine the effects of dual or pilot injection on reducing rates of combustion pressure rise and particulates/NO_x emissions.

2. 6.25 hour top ring wear tests should be continued to determine the effects of high frequency pressure oscillations on ring wear. Particulate measurements should also be included.

3. Further fundamental study is required to understand, the use of advanced injection techniques, the nature of particulate/NO_x formation over the entire premixed/diffusion combustion period.

4. Further fundamental study is required to determine the role of fuel-bound sulfur compounds and various aromatic structures on particulate formation.

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TABLE 1

PROPERTIES OF SYNTHETIC AND CONVENTIONAL CRUDES

	Synthetic Crude	Conventional Crude *
Gravity, °API	32	41
Density, kg/dm^3	0.865	0.820
Viscosity, cSt at 40 °C	3.0	2.9
Sulphur, wt %	0.08	0.2
Nitrogen, wt %	0.03	0.04
Hydrogen, wt %	12.6	13.6
Pour Point, °C	- 45	- 6
Distillate Yield, LV %		
I - C5	4	3
C5 - 195 °C	18	36
195 - 345 °C	47	31
345 - 560 °C	31	18
560 °C +	0	12

* - Canadian Federated Pipeline

TABLE 2

ENGINES TESTED IN CANADIAN OR RELATED FUTURE DISTILLATE FUELS-ENGINES RESEARCH PROGRAMS

ENGINE MFGR.	MODEL	COMB. CYCLE	DISPL/CYL. (in^3/l)	# of CYL.	ASP.	DIESEL CLASS	TEST FORMAT	TEST FACILITY	REF. #
DDC	3-71 *	2	71/1.16	3	NA(B)	H	L-P/C	NRC	2
DEUTZ	F1L511D *	4	50.3/.82	1	NA	H	L-P/C/E(G)/LT	DREO	4,5
DDC	6V53T *	2	53/.87	6	T	H	L-P/C/A	UofO	6,13
DDC	6V92TA *	2	92/1.5	6	T	H	L-P/C/E(G)/D	PC	7,8
CAT	3406	4	148.3/2.43	6	T	H	L-P/C/E(G)/LT	ESSO	9
CAT	3406	4	148.3/2.43	6	T	H	V-CS/WS/DR/FC	ESSO	9
Cummins	NTC400	4	142.2/2.33	6	T	H	V-CS/WS/DR/FC	ESSO	9
Mack	E6-350	4	112.7/1.83	6	T	H	V-CS/WS/DR/FC	ESSO	9
DDC	8V92TA	2	92/1.5	8	T	H	V-CS/WS/DR/FC	ESSO	9
Cummins	NTC400 *	4	142.2/2.33	6	T	H	L-P/C/E(G,P)	Cummins	10
Cummins	NTC400	4	142.2/2.33	6	T	H	L-P/C/E(G,P)	NRC	11
Bombardier	B-251 *	4	671.2/11.0	12	T	M	L-P/C/E(G)/D/LT	DND	3,12

ASP - Aspirated
NA - Naturally Aspirated
  (B) - Blown
H - High Speed Diesel
L - Laboratory
P - Performance
C - Combustion
NRC - National Research Council
E - Emissions
  (G) - Gaseous
  (P) - Particulates
LT - Low Temperature

DREO - Defence Research Establishment, Ottawa
A - Acoustics
UofO - University of Ottawa
D - Durability
PC - PetroCanada
V - Vehicle
CS - Cold Starting
WS - White Smoke
DR - Driveability
FC - Fuel Consumption
M - Medium Speed Diesel
DND - Department of National Defence

* - Tested the 1990's Experimental Fuel

Table 3 TEST FUEL SOURCE DESCRIPTION

Test Fuels used in fuel studies [3,12] for the Bombardier B-251 engine. The specification/compositional analysis is contained in Tables 4, 5 and 6. A description of the fuels together with the rationale for their selection is as follows:

Fuel "A" - The baseline or reference fuel is a conventional straight-run ASTM #2-D diesel fuel as supplied commercially in the Montreal area during the winter months.

Fuel "B" - A blend of conventional ASTM #2-D distillate with a heavy atmospheric gas oil (HGO) to provide a fuel with a distillation end point of about 400°C. This fuel specially blended by Ultramar Limited, was chosen to isolate and examine the effect of an extended distillation range on the engine.

Fuel "C" - A blend comprising 78 % of a distillate cut form a 50/50 mixture of conventional Western Canadian and tar sands crude and 22 % of hydrogen treated cracked stock. This provided a fuel containing a substantial level of aromatics and cracked components and typical of diesel fuel quality predicted for the 1990-2000 timeframe.

Fuel "D" - Gas Oil Side-Stream (GOSS). A 100 % tar sand distillate from Suncor at Fort McMurray as used by th two major Canadian railways as a locomotive fuel in Alberta. It is relatively high in aromatics and has a Cetane Number in the low 30's.

Fuel "E" - A blend of tar sand crude conponents comprising 50% gas oil side-stream and 50 % heavy unifined gas oil (HGO) from Suncor at Fort McMurray. This provided a fuel relatively high in aromatics, with a broad distillation range and high viscosity. This was seen as being a "worst case" distillate fuel.

Fuel "F" - An ASTM #2-D heating oil containing a substantial proportion of stabilized cracked stock (SCS). This fuel, provided by Imperial Oil Limited and referred to as an "economy distillate", is of particular interest for railway service.

Fuel "G" - A blend of conventional ASTM #2-D distillate with residual ASTM #6-D heating fuel. This provides a heavy fuel containing 25% residual components and is of particular interest for rail and marine applications in light of a possible economic advantage.

Test Fuels used in fuel studies with [4,5,6,7,11 and 13] the Deutz F1L511D, DDC 6V53T, DDC 6V92TA and the Cummins NTC 400.

A description of the fuel together with the rational for their selection is as follows:

Fuel "A" - Meets the Canadian General Standards Board (CGSB), 3-GP-30M standard for high stability diesel fuel and was selected as the reference fuel.

Fuel "B" - Is a blend of 78 % of a distillate cut form a 50/50 mixture of conventional western Canadian and tar sands crude and 22 % of hydrogen treated crated stock. This provided a fuel with a substantial amount of aromatics and racked components and is typical of diesel fuel quality predicted for the period 1990-2000.

TABLE 4

PHYSICAL/CHEMICAL TEST DATA

		A	B	C	D	E	F	G
1.	ASTM Colour (D1500)	3.0	5.0	-	<3.5	5.5	<3.0	D8.0
2.	API GRAVITY @ 60°F (D1298)	37.4	34.6	-	32.3	25.9	29.3	21.9
3.	SPEC. GRAV. @ 60/60°F (D1298)	0.8378	0.8519	.880	0.8639	0.8990	0.8800	0.9224
4.	Density @ 15°C, Kg/L (D1298)	0.8374	0.8515	.880	0.8634	0.8985	0.8795	0.9219
5.	Kinematic Viscosity, mm^2/s (D445) @ 40°C	2.23	3.53	2.81	2.36	6.09	2.24	17.20
6.	Distillation (D86), °C							
7.	I.B.P.	176	184	165	189	215	150	181
8.	10%	206	210	196	218	246	189	242
9.	50%	253	276	268	252	305	261	316
10.	90%	299	382	354	291	393	333	386
11.	F.B.P.	332	399	378	328	420	362	440(1a)
12.	Recovered, % Vol.	98.4	98.1	98.2	98.5	98.0	98.3	-
13.	Residue, % Vol.	1.6	1.9	1.5	1.5	2.0	1.5	-
14.	Loss, % Vol.	0.0	0.0	0.3	0.0	0.0	0.2	-
15.	Corrosion, 3h @ 100°C (D130)	No.1a	No.1a	No.1a	No.1a	No.1a	No.1a	No.1a
16.	Carbon Residue, 10% Bottoms, % Mass (D524)	0.13	0.13	.56	0.21	0.31	0.20	5.42(2)
17.	Ash, % Mass (D482)	0.000	<0.001	0.001	0.000	<0.001	0.000	0.008
18.	Water & Sediment, % Vol. (D1796)	<0.001	0.026	0.02	0.024	0.020	0.000	0.17
19.	Total Acid No. (D974)	0.04	0.62	0.08	0.05	0.05	0.05	3.88
20.	Sulphur, % Mass (X-Ray Fluor.)	0.13	0.71	0.59	0.08	0.38	0.24	0.86
21.	Nitrogen by Chemiluminescence, ppm by mass (4)	49	286	-	176	746	344	2200
22.	Smoke Point, (D1322)	18.3	15.3	12.1	15.0	12.7	10.7	Note (1)
23.	Refractive Index N_D^{20}	1.4660	1.4732	1.4935	1.4795	1.5002	1.4988	1.5009(1b)
24.	Molecular Weight	185	211	189.8	179	218	181	211
25.	Carbon, % Mass (by Difference i.e., 100-D3701)	86.7	86.8	87.8	87.3	87.8	88.2	<88.5(3)
26.	Hydrogen, % Mass (D3701)	13.3	13.2	12.2	12.7	12.2	11.8	11.5
27.	Carbon, % Mass (240 Analyzer) (4)	86.4	86.2	86.5	87.0	87.2	87.4	87.1
28.	Hydrogen, % Mass (240 Analyzer) (4)	13.3	13.2	12.0	12.8	12.2	11.7	11.6
29.	C/H Ratio (from 240 Analyzer Data) (4)	6.5	6.5	7.2	6.8	7.1	7.5	7.5
30.	Aniline Point, °C (D611)	61.8	66.8	46.9	44.6	51.2	37.7	62.0
31.	Cloud Point, °C (D2500)	-22	-5	-10	-45	-7	-12	Note (1)
32.	Pour Point, °C (D97)	-24	-15	-36	-45	-15	-21	-15
33.	Net Heat of Combustion, MJ/Kg (23.4M)	42.86	42.51	42.24	42.58	42.05	42.33	41.59
34.	Flash Point, °C (D93)	65	69	60.0	71	96	52	78

Notes:
(1) Due to black colour and presence of residuals, difficult to perform a complete test; (1a) FBP-D2887; (1b) Refractive index of dist.cut IBP-85%.
(2) Determined on sample as received.
(3) No corrections were made for sulphur, nitrogen and oxygen, etc.
(4) Determined by Energy, Mines and Resources.

TABLE 5

	A	B	C	D	E	F	G
Liquid Chromatography (D2007), % Mass							
Saturates (N_D^{20})	61.5(1.4474)	58.8(1.4522)	49.1	51.0(1.4559)	48.3(1.4652)	35.9(1.4485)	37.9(1.4589)
Polar Compounds	0.3	1.5	0.8	0.5	1.8	0.6	17.1
Aromatics (N_D^{20})	38.2(1.5304)	39.7(1.5428)	50.1	48.5(1.5196)	49.9(1.5403)	63.5(1.5567)	45.0(1.5699)
FIA (D1319), % Volume							
Saturates	72.0	73.7	58.2	54.5	47.7	47.5	Note (1)
Olefins	0.7	0.8	1.3	1.0	1.3	0.7	Note (1)
Aromatics	27.3	25.5	40.5	44.5	51.0	51.8	Note (1)
ndM (D3238), %							
Paraffinic Carbons, C_P	49.6	48.1	42.5	39.2	40.1	43.0	-
Naphthenic Carbons, C_N	37.4	36.3	30.3	41.6	37.1	23.6	-
Aromatic Carbons, C_A	13.0	15.6	27.2	19.3	22.8	33.4	32.18(2)
Naphthenic Rings, R_N	0.88	0.94	.88	1.09	1.26	0.61	-
Aromatic Rings, R_A	0.31	0.36	.64	0.42	0.63	0.75	-
Total Rings, R_T	1.19	1.30	1.52	1.51	1.89	1.36	-
Proton NMR (norm. to 100%), % Mass							
Paraffins	61.8	73.7	51.1	52.8	48.2	42.0	47.4
Aromatics	38.2	26.3	48.9	47.2	51.8	56.0	52.6
% C_2	49.1	52.8	36.2	39.7	40.0	30.1	40.4
% C_3	18.4	21.4	13.6	17.6	15.4	10.7	12.4
% C_A	18.3	17.2	33.6	27.2	23.5	39.1	28.2
Modified Liquid Chromatography % Mass							
Mono-Aromatics	19.0	18.3	22.6	33.8	29.5	34.0	18.9
Di-Aromatics	8.5	9.2	11.9	5.0	9.5	14.5	13.6
Poly Aromatics & Polar Compounds	0.8	5.0	9.6	1.6	8.8	5.9	22.3
ASTM Cetane Index (D976-66/IP218)	49.8	50.5	38.5	39.5	40.0	36.3	35.5
ASTM Cetane Index (D976-80)	48.0	48.0	40.0	39.5	39.5	37.0	35
Cetane Number (D613)	44.7	47.8	34.7	33.4	34.6	31.0	37.0(5)
CGSB Cetane Index (3)	45.3	48.5	35.3	34.4	35.9	26.6	35.0
Estimated Cetane Number (4)	44.0	47.2	34.8	34.7	36.5	30.1	39.9

Notes
(1) The fuel is not well suited to FIA analysis due to the black colour and high F.B.P.
(2) Determined by ^{1}H NMR
(3) The Canadian General Standards Board is proceeding with the standardization of this index. A report describing the development of the index is presented in SAE paper No. 841344, October 1984. The CGSB Cetane Index is based on density, boiling range, aniline point and viscosity.
(4) Based on the carbon type distribution by proton NMR as presented in SAE paper No. 841341.
(5) Due to poor combustion stability, the NRC Constant Compression Ratio Method was employed.

Table 6

Fuel Analysis

	NRC 1990	SHELL REF FUEL A DIESEL #2	"30%" BLEND	"50%" BLEND	"60%" BLEND
% Bunker, by Calculation		-	25	42	50
Viscosity 40°C, cSt	2.78	2.19	4.75	9.90	4.45
50°C, cSt	-	-	3.74	7.35	10.45
100°C, cSt	-	-	1.69	2.77	3.49
Density, 15°C, Kg/L	0.878	0.838	0.951	0.952	0.951
Condradson Carbon, % (D189) (10% Bottoms)	0.20	0.12	2.43^{+}	4.03^{+}	4.43^{+}
Flash Point, °C	60	65	-	-	-
Corrosion to Copper (D130)	-	1A	-	-	-
Cloud Point, °C	-10	-24	-	-	-
Pour Point, °C	-37	-30	-	-	-
Sulphur, %	0.5	0.14	0.81	1.02	1.20
Vanadium, ppm	-	-	83.4	117.3	131.5
Sodium, ppm	-	-	30.0	-	-
Heat of Combustion: (Gross)					
MJ/Kg	44.93	45.72	43.97	43.93	43.85
MJ/L	39.44	38.31	41.82	41.76	41.75
BTU/lb	19,356	19,697	18,905	18,886	18,853
BTU/Imp.Gal.	169,935	165,066	179,828	179,527	179,480
Distillation:					
10% over, °C	198	203	-	-	-
50% over, °C	268	253	-	-	-
90% over, °C	354	302	-	-	-
Recovery, %	-	98	-	-	-

+ - As Received

Table 7

Fuel Characteristics

Fuel Property	A	B
Density at 15°C, kg/L (D1298)	0.8398	0.8779
Kinematic Viscosity @ 40°C, cST (D445)	2.41	2.78
Distillation (D86), °C		
IBP, °C	172	166
10%	203	198
50%	258	268
90%	324	354
FBP, °C	352	383
Recovery, % Vol.	98.0	98.1
Residue, % Vol.	1.9	1.8
Flash Point, °C (D93)	57	60
Smoke Point (D1322)	17.0	12.1
Aniline Point, °C (D611)	63	46.9
Refractive Index,	1.4677	1.4935
ASTM Cetane Index (D976-66/IP218)	50.4	38.5
ASTM Cetane Index (D976-80)	48.2	40.0
CGSB* Cetane Index	47.1	35.3
Cetane No. (D613)	46.9	35.5
Hydrogen, % Mass (D3701)	13.4	12.2
Hydrogen, % Mass (240 Analyzer)	13.3	12.0
Carbon, % Mass (240 Analyzer)	86.3	86.5
Nitrogen by Chemiluminescence, PPM (Mass)	240	-
Sulphur, % Mass (D129)(D1552)	0.21	0.51
Avg. Molecular Weight	190.4	189.8
Heat of Combustion, Gross, BTU/lb (D240)	19,610	19,185

*Canadian General Standards Board

Table 8

Compositional Analyses

Fuel Property	A	B
Liquid Chromatography (D2007) % mass		
Saturates	68.9(71.2)*	49.1(52.7)*
Polar CPDS	0.5	0.8
Aromatics	30.6	50.1
FIA (D1319); % vol.		
Saturates	78.2	58.2
Olefins	0.9	1.3
Aromatics	20.9	40.5
n-d-M (D3238)+		
Paraffinic Carbons, % C_P	49.5	42.5
Naphthenic Carbons, % C_N	36.3	30.3
Aromatic Carbons, % C_A	14.2	27.2
Naphthenic Rings, R_N	0.89	0.88
Aromatic Rings, R_A	0.33	0.64
Total Rings, R_T	1.22	1.52
Mass Spec. (PONA)+, % mass		
Paraffins	31.1	26.3
Olefins	0.0	0.0
Naphthenes	40.2	33.6
Aromatics	28.7	40.1
GC-Mass Spec., % mass		
n-Alkanes	43.4	34.9
ISO-Alkanes	25.9	14.2
Cyclo Alkanes	9.9	4.5
Total Paraffins	79.2	53.6
Total Aromatics	20.5	46.0
Polars & Unidentified	0.3	0.4
Proton NMR, % mass		
Paraffins	78.9	51.1
Aromatics	21.1	48.9
Carbon Groups		
% C_α-alpha-alkyl CH_2,CH_3	6.5	13.4
% C_2-paraffinic CH,Ch_2	52.0	36.2
% C_3-paraffinic CH_3	29.5	13.6
% C_A-aromatic ring carbon	15.5	33.7

*% Vol.

+ The n-d-M (D3238) and Mass Spec. (PONA) methods overestimate the (cyclo alkane) content of the fuels.

Table 9 - Fuel Comparison between the Reference Fuel and the 1990's Experimental Fuel

Fuel	ρ	υ visc.	10 % Pt	50 %	90 %	H % mass	$\overline{MW}$	H. Comb	Arom. FIA	Arom. D2007	Arom. DNMR
Ref. Fuel ↓ 1990's	↑	↑	↓	↑	↑	↓	↓	↓	↑	↑	↑
Change %	4.5	15.3	3.5	3.9	9.2	9.8	0.3	2.2	45.9	63.7	132.0

Table 10 - Performance/Combustion - Emissions/Durability Summary for the DDC 6V92TA (max. speed/load)

	Performance		Combustion - Emissions							Durability (500 hr.)			
Fuel	Output (500 hr.)	SFC	ID	Pc	$\frac{d\,Pc}{d\,\theta}$	Smoke (BSN)	HC	CO	NO_x	Dep.	Brg. Wear	TRW	Liner Wear
Ref. Fuel ↓ 1990's	↑	↑	↑	↑	↑	↑	↓	↓	↑	↑	↑	↑	↑
Change %	0.7	1.4	30	1.2	97	200	17	23	5.7	2-5	150	230	VS

vs - 0-2%

Table 11 - Performance/Combustion Summary for the DDC 6V53T (max. speed/load)

	Performance		Combustion			
Fuel	Output	SFC	ID	Pc	$\frac{d\,Pc}{d\,\theta}$	$\frac{d\,Pc}{d\,\theta}$ (inst.)
Ref. Fuel ↓ 1990's	↑			↑	↑	↑
Change %	6.0	0	0	3.0	20	50

Table 12 - Performance/Combustion - Emissions Summary for the Cummins NTC 400 (max. speed/load)

	Performance		Combustion							
Fuel	Output	SFC	ID	Pc	$\frac{d\,Pc}{d\theta}$	Smoke (BSN)	Part. P_t / SEF	HC	CO	NO_x
Ref. Fuel ↓ 1990's	NA	↑	↑		↓	↑	↑ / ↓	↓		↑
Change %		1.0	5.0	0	4.0	30.0	15.0 / 5.0	10	0	1.0

Table 13 - Performance/Combustion - Emissions Summary for the Bombardier B-251 (max. speed/load)

	Performance		Combustion						
Fuel	Output	SFC	ID	Pc	$\frac{d\,Pc}{d\theta}$	Smoke (BSN)	HC	CO	NO_x
Ref. Fuel ↓ 1990's	NA	↑	↑		↑	↓	↓		↑
Change %		4.0	10	0	25	30	5	0	40

Table 14 - Fire Ring Wear Rate

Injector 9B90		milligrams/hour
Conventional	Advanced	1.05
45.9 Cetane	Base	0.35
	Retarded	1.01
NRC Fuel 1	Advanced	2.34
34.5 Cetane	Base	1.75
	Retarded	2.60
NRC Fuel 2	Advanced	4.60
30.0 Cetane	Base	3.39
	Retarded	6.27

Injector 9G85		milligrams/hour
Conventional	Advanced	0.34
45.9 Cetane	Retarded	0.65
NRC Fuel 1	Advanced	1.34
34.5 Cetane	Retarded	2.65
NRC Fuel 2	Advanced	3.16
30.0 Cetane	Retarded	5.14

Injector N90		milligrams/hour
Conventional	Advanced	0.83
45.9 Cetane	Retarded	1.02
NRC Fuel 1	Advanced	3.50
34.5 Cetane	Retarded	2.90
NRC Fuel 2	Advanced	5.42
30.0 Cetane	Retarded	5.56

Figure 6 : Exhaust Valve Failure Due to Residual Fuel Vanadium/Sodium Corrosion

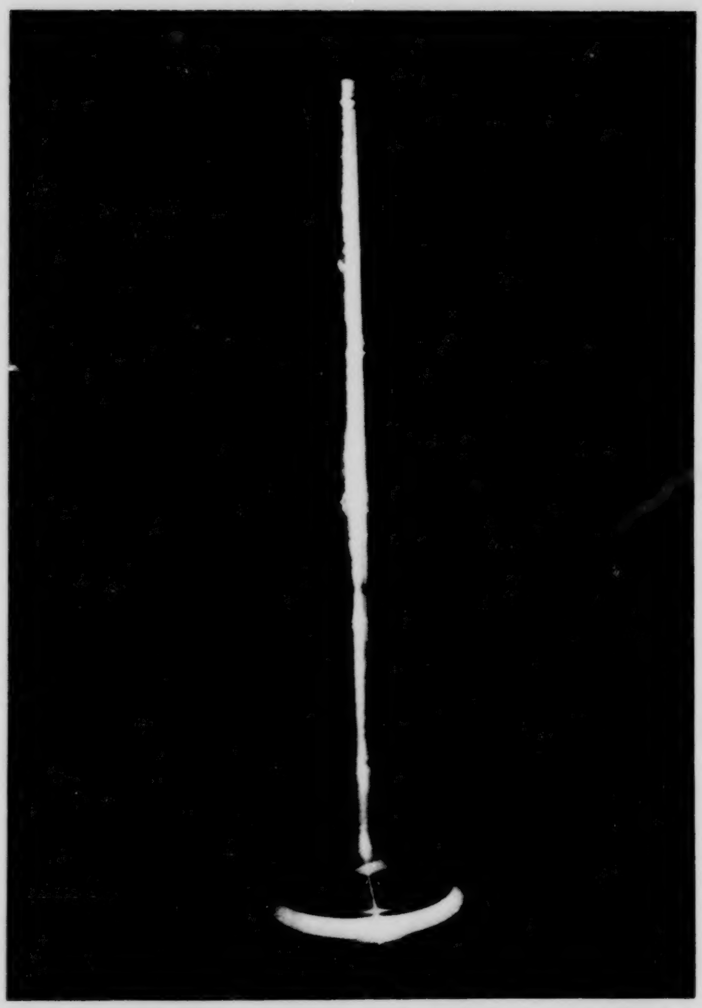

Figure 7 : A Prototype Exhaust Valve Incorporating a Monolithic Ceramic Seat Face

A REVIEW OF THE EFFECTS OF FUTURE CANADIAN DISTILLATE FUELS ON HIGH/MEDIUM SPEED DIESELS

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THE OBJECTIVES

FOR THIS R&D WITH CANADIAN 1990'S FUELS

- Determine the Effects of Fuel Cetane Number Reduction on Diesel Operational /Performance /Combustion /Durability Characteristics.
- Determine the Effects of other Fuel Properties/Structural Composition on Engine Behaviour

RATIONALE FOR OBJECTIVES

- Reducing CGSB Minimum Cetane from 40 to 37 or 35 Could Potentially Produce a National Cost Savings. (For Conventionally and Tar Sands Derived Fuels)
- Ease Increasing Canadian Demand for Middle Distillate Fuels

CANADIAN 1990's EXPERIMENTAL FUELS

- Canadian 1990's and beyond Experimental Fuel

78% of a Distillate Cut from a 50/50 Mixture of Conventional and Tar Sands Crude

22% Hydrogen Treated Cracked Stock

Property / Fuel	Ref. Fuel A	1990's Exp. Fuel B
Density (D1298)	0.837	0.880
Kin. Visc., cSt (D445)	2.23	2.81
Flash Pt., °C (D93)	65.0	60.0
Cloud Pt., °C (D2500)	-22	-10
Pour Pt., °C (D97)	-24	-36

- A Number of other Test Fuels with Specific Properties Tailored to Study their Effects on Engines (i.e. T_{90}, Natural Cetane vs. Ignition Improver, Aromatic Type, Naphthenic Type, etc.)

- Reference Fuel usually met CGSB 3-GP-30M Standard for High Stability Diesel Fuel

Property / Fuel	Ref. Fuel A	1990's Exp. Fuel B
Distillation, °C (D86)		
IBP	176	165
10%	206	196
50%	253	268
90%	299	354
FBP	332	378
Carbon Res., % Mass 10% Bottoms (D529)	0.13	0.56

Property \ Fuel	Ref. Fuel A	1990's Exp. Fuel B
Sulphur, % Mass (XRFL)	0.13	0.56
C/H Ratio (240A)	6.5	7.2
Aromatics, % Mass (PNMR)	38.2	48.9
Cetane No. (D613)	44.7	34.7

Table 9 - Fuel comparison between the reference fuel and the 1990's experimental fuel

Fuel	ρ	ν visc.	10 % Pt	50 %	90 %	H % mass	MW	H. Comb	Arom. FIA	Arom. D2007	Arom. DNMR
Ref. Fuel ↓ 1990's	↑	↑	↓	↑	↑	↓	↓	↓	↑	↑	↑
Change %	4.5	15.3	3.5	3.9	9.2	9.8	0.3	2.2	45.9	63.7	132.0

DIFFICULTIES WITH SPECIFICATION ANALYSIS

- Aromatic Determination (FIA, D2007, PNMR)
- Cetane Index (CGSB, ASTM)
- Hydrogen Content (D3701, EMR 240 ANAL.)

ENGINE EXPERIMENTS

- DDC 3-71
- NTC 400
- Deutz F1L511D
- DDC 6V92TA
- DDC 6V53T
- Bombardier B-251
- CAT 3406
- Truck/Engine Combinations

}Tested the 1990's Experimental Fuel

Table 11 - Performance/Combustion - Emissions/Durability Summary for the DDC 6V92TA (max. speed/load)

	Performance		Combustion - Emissions							Durability (500 hr.)			
Fuel	Output (500 hr.)	SFC	ID	Pc	$\frac{dPc}{d\theta}$	Smoke (BSN)	HC	CO	NO_x	Dep.	Brg. Wear	TRW	Liner Wear
Ref. Fuel ↓ 1990's	↑	↑	↑	↑	↑	↑	↓	↓	↑	↑	↑	↑	↑
Change %	0.7	1.4	30	1.2	97	200	17	23	5.7	2-5	150	230	VS

Dep. - deposits
TRW - top ring wear
VS - 0-2%

Table 12 - Performance/Combustion Summary for a DDC 6V53T (max. speed/load)

	Performance		Combustion			
Fuel	Output	SFC	ID	Pc	$\frac{dPc}{d\theta}$	$\frac{dPc}{d\theta}$ (inst.)
Ref. Fuel ↓ 1990's	↑			↑	↑	↑
Change %	6.0	0	0	3.0	20	50

Inst. - Instantaneous

Table 13 - Performance/Combustion - Emissions Summary for the Cummins NTC 400 (max. speed/load)

	Performance		Combustion							
Fuel	Output	SFC	ID	Pc	$\frac{dPc}{d\theta}$	Smoke (BSN)	Part. P_t / SEF	HC	CO	NO_x
Ref. Fuel ↓ 1990's	NA	↑	↑		↓	↑	↑ / ↓	↓	↑	↑
Change %		1.0	5.0	0	4.0	30.0	15.0 / 5.0	10	20	3.0

Table 14 - Performance/Combustion - Emissions Summary for the Bombardier B-251 (max. speed/load)

	Performance		Combustion						
Fuel	Output	SFC	ID	Pc	$\frac{dPc}{d\theta}$	Smoke (BSN)	HC	CO	NO_x
Ref. Fuel ↓ 1990's	NA	↑	↑		↑	↓	↓		↑
Change %		4.0	10	0	25	30	5	0	40

FINDINGS

THE 1990'S EXPERIMENTAL FUEL HAD LITTLE EFFECT ON :

- Engine/Vehicle Operability
- Fuel Consumption
- Output Power
- Peak Cylinder Pressure (TC)
- Unburned Hydro Carbons
- Carbon Monoxide
- Combustion Chamber & Exhaust System Deposits
- Cold Starting

FINDINGS

THE 1990's EXPERIMENTAL FUEL CAUSED INCREASES TO :

- Total Particulate Emissions (NTC 400)
- Nitrogen Oxide Emissions
- Rates of Combustion Pressure Rise
- Slipper Bearing Wear (6V92TA)
- Top Ring Wear (6V92TA)
- Cold Idle Roughness
- White Smoke Production

RATES OF COMBUSTION PRESSURE RISE

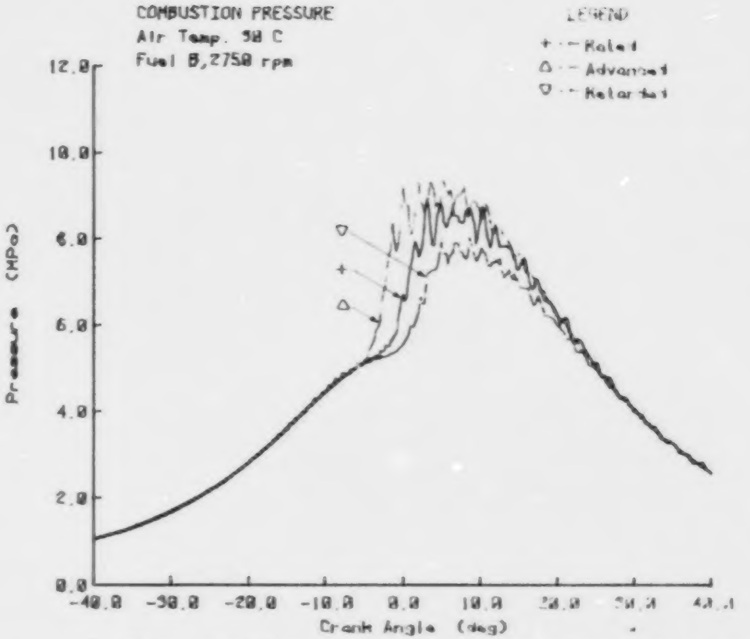


Figure 1 - Combustion Pressure Traces for a Deutz F1L511D Single Cylinder Direct Injection Diesel Engine

STUDY OBJECTIVE

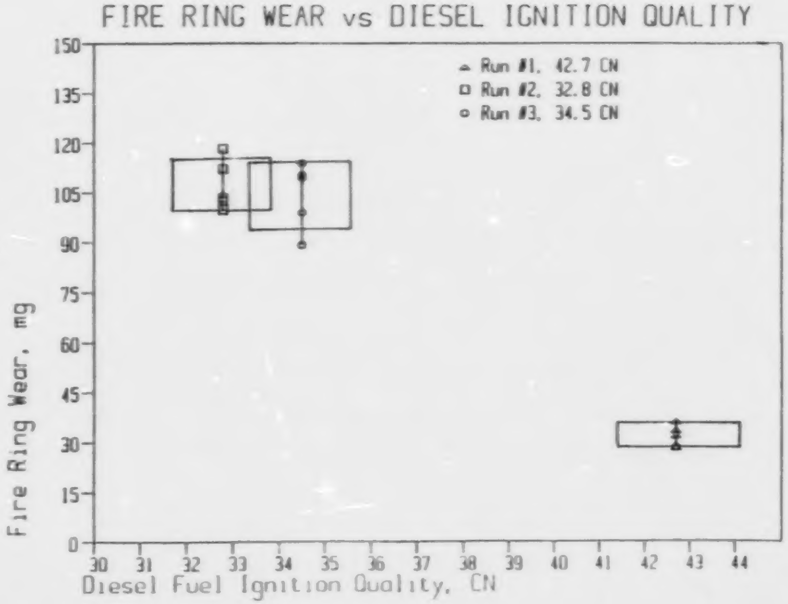
To assess wear and deposit accumulation in a medium truck - sized diesel engine (typical of military applications) over a 500 hour period using low cetane fuels .

FIRE RING WEAR (AVG.)

500 Hr. Run #	Wht. Loss (mg)
1	31.8
2	104.2
3	107.2

FUEL BLEND COMPONENTS

500 hour Run #	Comp. A	Comp. B	Cetane #
1	Diesel Reference Fuel		42.7
2	60	40	32.8
3	65	35	34.5



SLIPPER BEARING WEAR (AVG.)

500 Hr. Run #	Wht. Loss (mg)
1	234
2	500
3	584

FIRE RING WEAR IMPLICATIONS

- DDA's experience indicates that the substantial ring wear would reduce engine life by approximately 70 % for this engine type (10,000 hrs to 3,000 hrs)
- For military applications where an engine rebuild is done at approx. 2,000 hrs , installation of some cylinder kits would be required
- Hence , increased rebuild costs

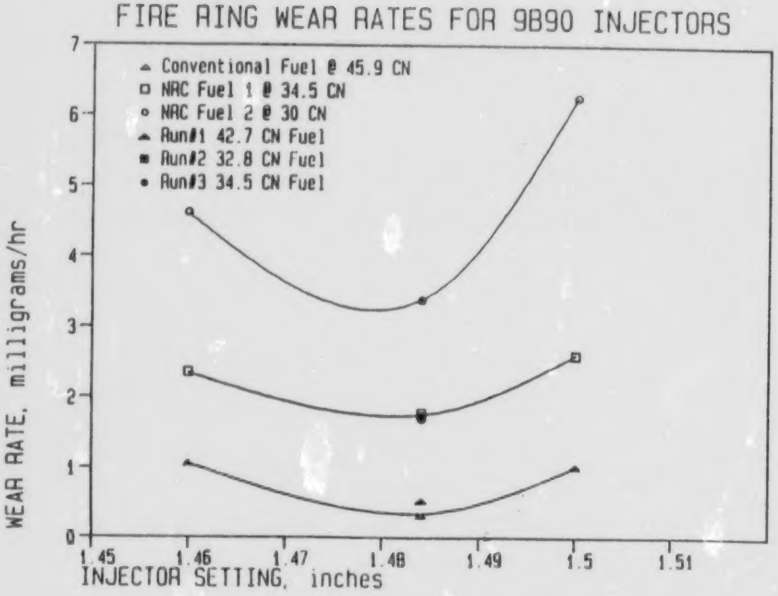
6.25 HOUR DIESEL DURABILITY TESTS

- 21 - 6.25 hour max. Speed/Power Tests on 6V92TA at Petro-Canada
- Lubricating Oil was analyzed to determine Top Ring Chromium Plating Weight Loss

TEST OBJECTIVES

To Determine the Effects of Combustion Pressure Rise Reduction on Top Ring Wear by ;

- Varying Fuel Cetane Levels (45.9, 34.5, 30.0)
- Varying Injector Timing (advanced, base, retarded)
- Varying Injector Type (9B90, 9685, N90)

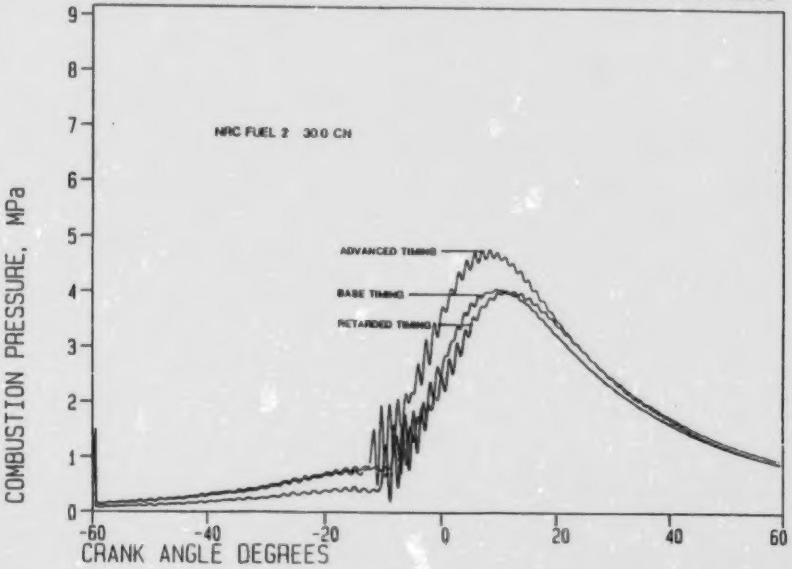


COMBUSTION PRESSURE RISE REDUCTION

- 6V53T had one Injector with Electronic Control (University of Ottawa)
- For 1990's Fuel (with dual injection) Rates of Combustion Pressure Rise were reduced to a Value Lower than that of Reference Fuel
- High Frequency Vibrations were Substantially Reduced

Figure 2

COMBUSTION PRESSURE vs CRANK ANGLE FOR INJECTOR 9B90



PARTICULATE EMISSIONS

Cummins NTC 400 - NRC

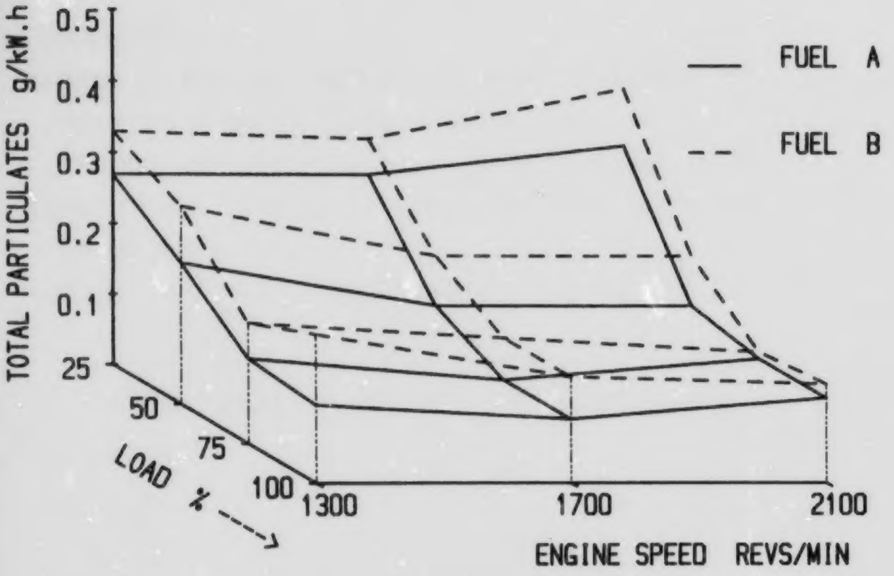


Figure 3: TOTAL PARTICULATES

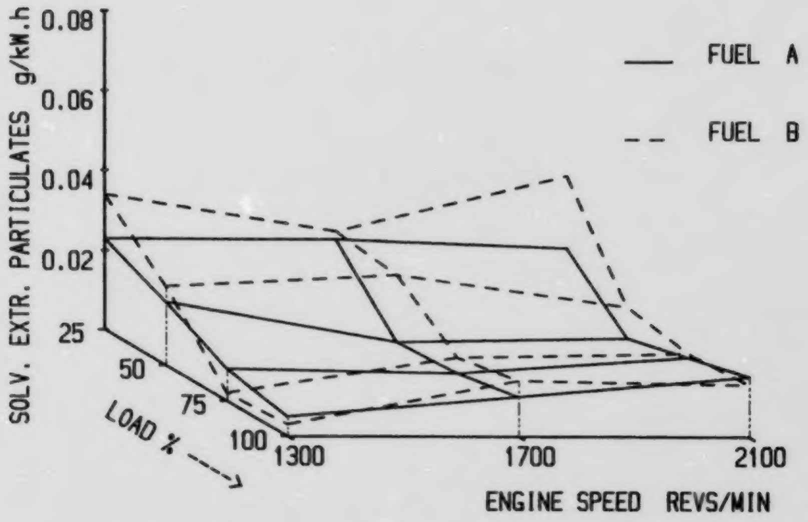
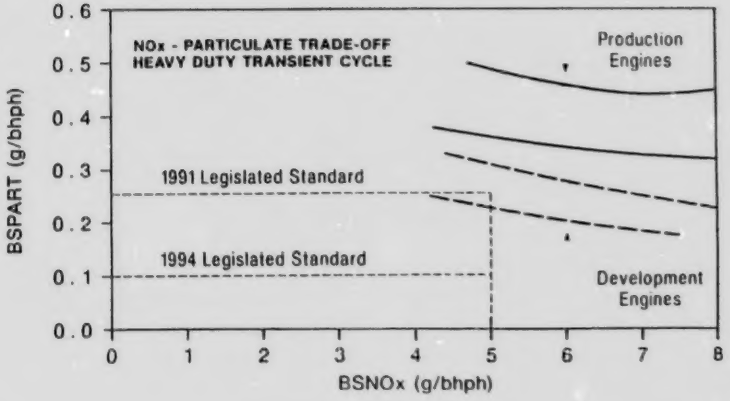


Figure 4: SOLVENT EXTRACTABLE PARTICULATES

- **Total Particulate Emissions increased approx. 20% over the Engine Operating Range for the 1990's Fuel**
- **Higher Aromatic and Sulphur Contents are likely responsible**
- **Canadian EMR/PACE Study and the US CRC VE-1 Program will assist in determining the influence of Sulphur and Aromatic Type on Particulates**
- **NRC is also investigating the Influence of Fuel Structure on Particulate and Soot Formation**

OXIDES OF NITROGEN



- FIGURE 5 -

Trade Offs

NO_x - Particulates
NO_x - HC
NO_x - BSFC

Constraints

↑ Pc & T ↑ NOx
↑ Rate of Comb. ↑ NOx
↑ A/F Mixing ↓ PART ↑ NOx

Q - What is the Relationship between NO_x to Pre-Mix Fuel Quantity ?

or

How does NO_x Formation vary over Combustion Period (Pre- Mix/Diffusion) ?

NO_x FINDINGS

For all Engines tested with 1990's or similar Test Fuels , the NO_x Levels increased by approx. 10 - 20% over the Operating Range

- 6 Test Fuels were blended to vary :
  Natural Cetane, Ignition Improved Cetane, T_{90}, Synthetic vs Conventional Crude Sources

- CAT 3406

↑ Cetane (N, I I) ↑ Cold Startability ↓ White Smoke
↑ Cetane (N, I I) ↑ Idling
↑ Cetane (N, I I) — Black Smoke — HC — CO
↑ Cetane (N, I I) ↓ $\frac{d\,Pc}{d\theta}$ ↓ NO_x

N - natural, I I - Ignition Improver

LOW TEMPERATURE CAPABILITY OF DIESELS USING LOW CETANE FUELS

(Esso Canada Ltd.)

- CAT 3406

↑ T_{90} — Cold Startability — ID ↑ White Smoke
↑ T_{90} — Black Smoke — NO_x
↑ T_{90} ↓ HC ↑ CO

Conv. vs Synthetic : Synthetic ↓ NO_x

TRUCK/DIESEL COLD STARTING

Engine Design had Greatest Effect on :

- Cold Startability
- White Smoke
- Cold Idle Roughness
- Driveability

↑ T90 ↑ White Smoke

↑ Cetane (Nat) ↓ White Smoke

↑ Cetane (Ign. Imp.) ↓ White Smoke

Conv. vs Synthetic : — White Smoke

The Effects of Fuel to Driveability was Problematic on only one Truck at - 25 °C

↑ Fuel Viscosity ↓ Driveability

MEDIUM SPEED DIESEL DURABILITY STUDIES

INDUSTRY/CANADIAN FEDERAL GOVERNMENT STUDY

PHASE I - Performance and Emissions Tests
on a Bombardier/ALCO 251-12 cyl diesel
with 6 Canadian Experimental Fuels

PHASE II - Durability Testing of the 251 engine
with two of the experimental fuels

Fuel Property	A	C	G
Density (D1298)	0.837	0.880	0.922
Kin., Visc., cST (D445)	2.23	2.81	17.20
Flash Pt., °C (D93)	65.0	60.0	78.0
Cloud Pt., °C (D2500)	-22	-10	-
Pour Pt., °C (D97)	-24	-36	-15

Fuel Property	A	C	G
Distillation, °C (D86) IBP	176	165	181
10%	206	196	242
50%	253	268	316
90%	299	354	386
FBP	332	378	440+
Carbon Res., % Mass 10% Bottoms (D529)	0.13	0.56	5.42

Fuel Property	A	C	G
Sulphur, % mass (XRFL)	0.13	0.56	5.42
C/H Ratio (240A)	6.5	7.2	7.5
Aromatics % Mass (PNMR)	38.2	48.9	52.6
Cetane No. (D613)	44.7	34.7	37.0
Vanadium - PPM Sodium - PPM	- -	- -	83.4 30.0

Fuel "G"

- 500 Hour Comparative Differences Rel. to Fuel "C"
  - Engine Ex. Valve Failure 442 hour Pt.
  - ↑ Inj./Fire Deck Deposits
  - Slight Laquering of Piston Skirts
  - Thin Layer of Brownish Yellow Deposits Ex. Manifold
  - ↑ Carbonized Lub Oil Deposits on Ex. Valve

RECOMMENDATIONS - FUEL "G"

- Consider Inj. Tip Heating or Insulation to Reduce Idle Deposits
- Consider Ceramic Coated/Monolithic Ex. Valves to Reduce Vanadium/Sodium Attack
- Conduct Further Residual Fuel Blend Tests on NRC/Bombardier B-2400 Single Cylinder Research Engine. Consider 30, 50 and 60% Blends at Higher Combustion Temperatures

CONCLUSIONS

1. For the diesel engines indicated in Table 2, use of the 1990's fuel with higher aromatic content (mono, di and polyaromatics; Table 5 and 8) has resulted in only minor changes to:

- **Engine/Vehicle Operability**
- **Fuel Consumption**
- **Output Power**
- **Peak Cylinder Pressure - TC**
- **Unburned Hydrocarbons**
- **Carbon Monoxide**
- **Deposits (Combustion Chamber and Exhaust)**
- **Cold Starting**

TC - Turbocharged

2. For the diesel engines indicated in Table 2, use of the 1990's fuel with higher aromatic content (mono, di and polyaromatics; Table 5 and 8) has resulted in significant increases to:

- **Ignition Delay**
- **Rates of Combustion Pressure Rise**
  - **- Top Ring Wear (6V92TA)**
  - **- Slipper Bearing Wear (6V92TA)**
- **Peak Cylinder Pressures - NA**
- **Total Particulate Emissions (NTC 400)**
- **Nitrogen Oxide Emissions**
- **Low Temperature - Idle Roughness**
  - **- White Smoke**

( ) - brackets indicate conclusions are based on tests for one engine family, NA - Normally Aspirated

3. For the DDC 6V53T Diesel with the 1990's fuel, dual or pilot injection decreased rates of combustion pressure rise to values lower than those of the reference fuel.

4. Top ring wear on the 6V92TA appeared to correlate to rates of combustion pressure rise for advanced and reference injection timing.

Increased wear for the retarded injection did not correlate with rates of combustion pressure rise. These wear rates appeared to be influenced by the location of high frequency oscillations relative to top dead centre.

RECOMMENDATIONS

1. Further study is required to determine the effects of dual or pilot injection on:
   - Reducing rates of combustion pressure rise
   - Particulate/NO_x emissions

2. 6.25 hour top ring wear tests should be continued to determine the effects of high frequency pressure oscillations on ring wear.

Particulate measurements should also be included.

3. Further fundamental study is required to understand, for advanced injection techniques, the nature of particulate/NO_x formation over the premixed/diffusion combustion period.

4. Further fundamental study is required to determine the role of fuel bound sulfur compounds and various aromatic structures on particulate formation.

ENGINE AND CONSTANT VOLUME BOMB STUDIES OF DIESEL IGNITION AND COMBUSTION

BY
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WORK FUNDED JOINTLY BY U.S. ARMY BELVOIR RESEARCH,
DEVELOPMENT AND ENGINEERING CENTER AND THE
U.S. DEPARTMENT OF ENERGY, ALTERNATIVE FUELS
UTILIZATION BRANCH

SUMMARY OF PRESENTATION

- OVERALL OBJECTIVES
- PROBLEMS WITH CURRENT METHODS
- EXPERIMENTAL APPARATUS
- RESULTS
- NEW DATA

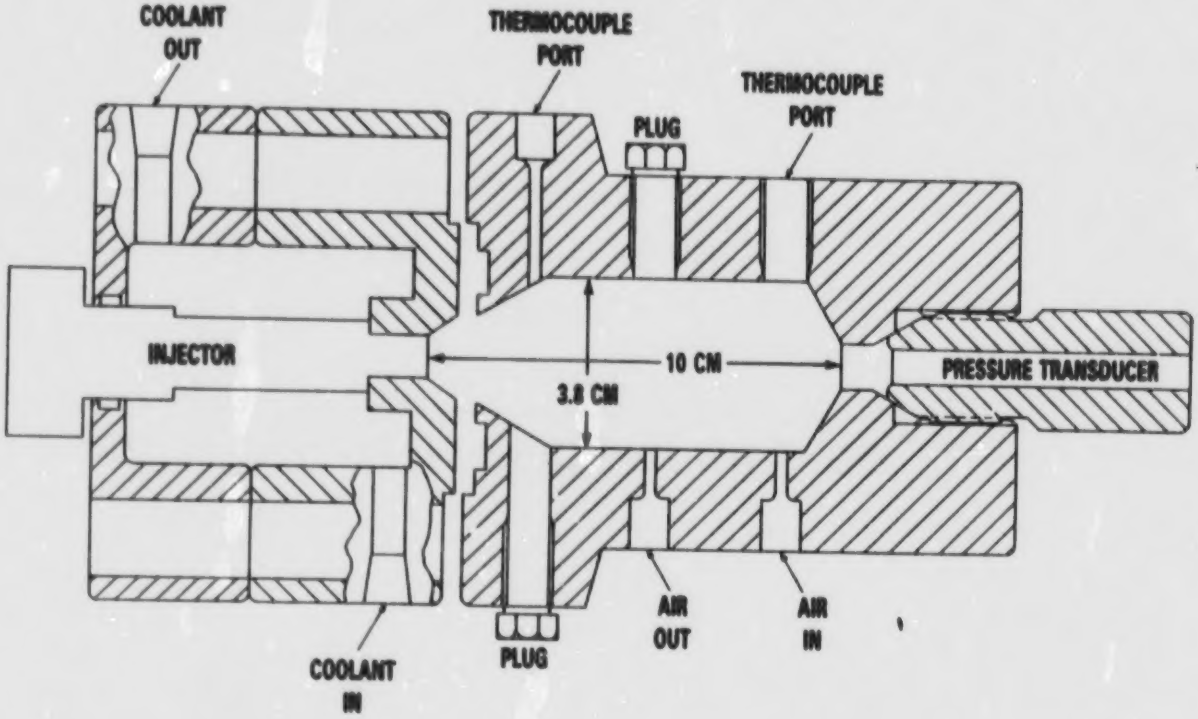
OBJECTIVES

- DEVELOP NEW METHOD FOR RATING IGNITION QUALITY OF DIESEL FUELS
- DEVELOP FUNDAMENTAL UNDERSTANDING AND BASIS FOR NEW METHOD

PROBLEMS WITH CURRENT METHOD

- METHOD BASED ON TWO NON-REPRESENTATIVE REFERENCE FUELS
- METHOD IS TOO EMPIRICAL, NO FUNDAMENTAL DEFINITION
- METHOD UTILIZES A NON-REPRESENTATIVE ENGINE

IGNITION/COMBUSTION BOMB


COOLANT OUT
THERMOCOUPLE PORT
PLUG
THERMOCOUPLE PORT
INJECTOR
10 CM
3.8 CM
PRESSURE TRANSDUCER
COOLANT IN
PLUG
AIR OUT
AIR IN

TEST CONDITIONS

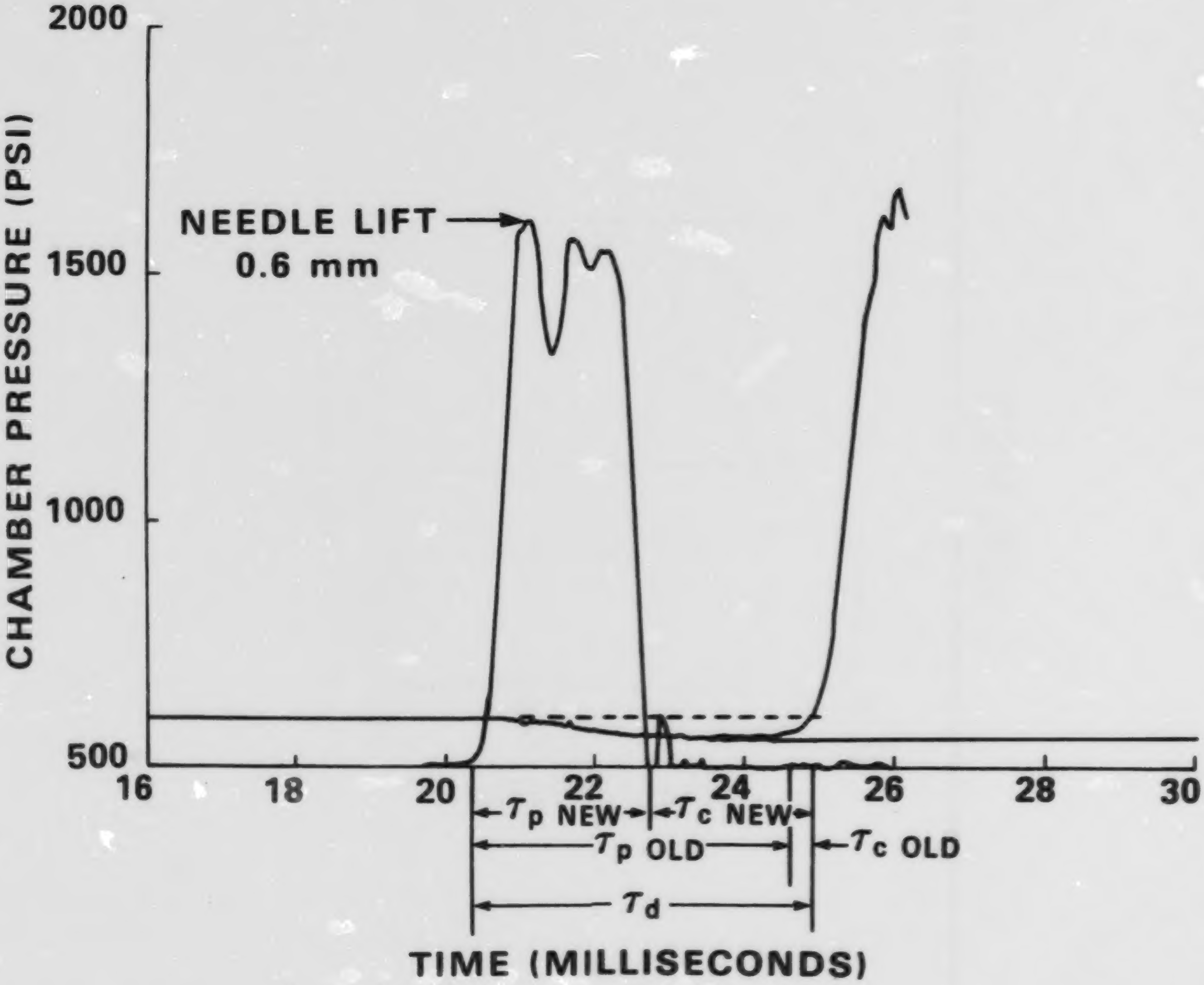
INITIAL PRESSURE–2 MPa

INITIAL TEMPERATURE–371°C
427°C
482°C

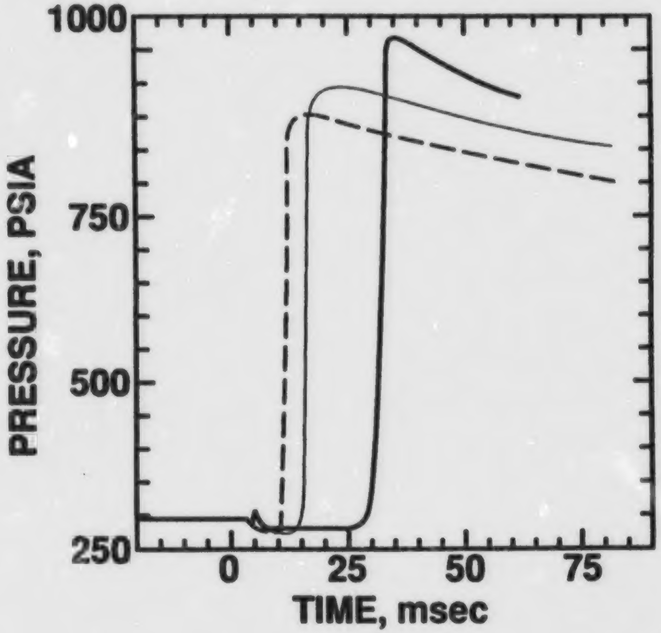
TEST FUELS

BLENDS OF HEXADECANE IN HEPTAMETHYLNONANE:	D-613 CN
0% HEX	15
5% HEX	19
10% HEX	24
20% HEX	32
30% HEX	41
40% HEX	49
50% HEX	58
100% HEX	100
TEST FUELS	
1	46
2	44
3	49
4	42

COMBUSTION PRESSURE AND NEEDLE LIFT TRACES FOR 75% HEXADECANE, 25% HEPTAMETHYLNONANE BLEND



30% HEX



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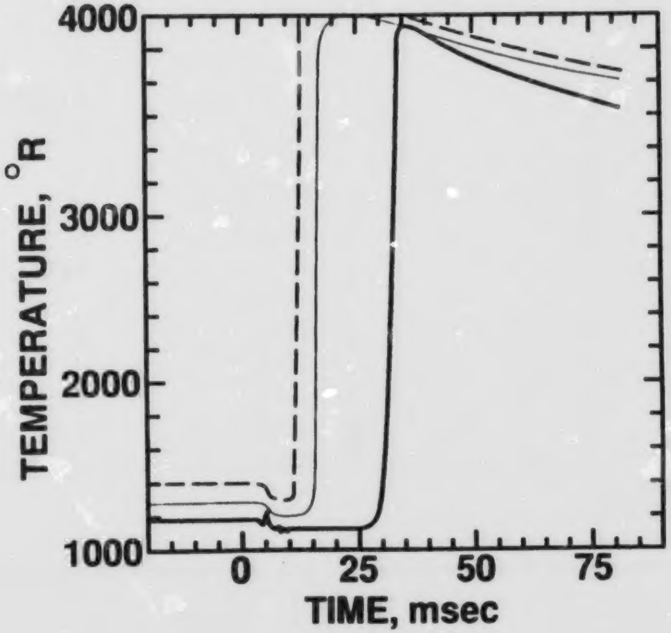

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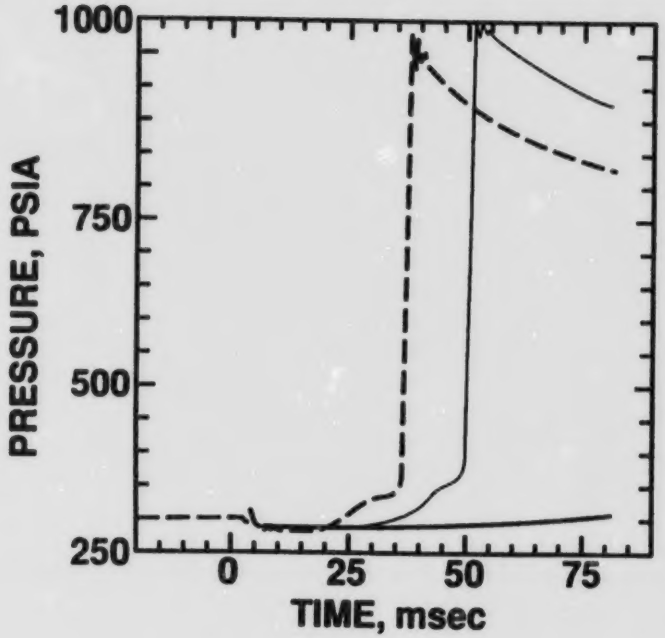

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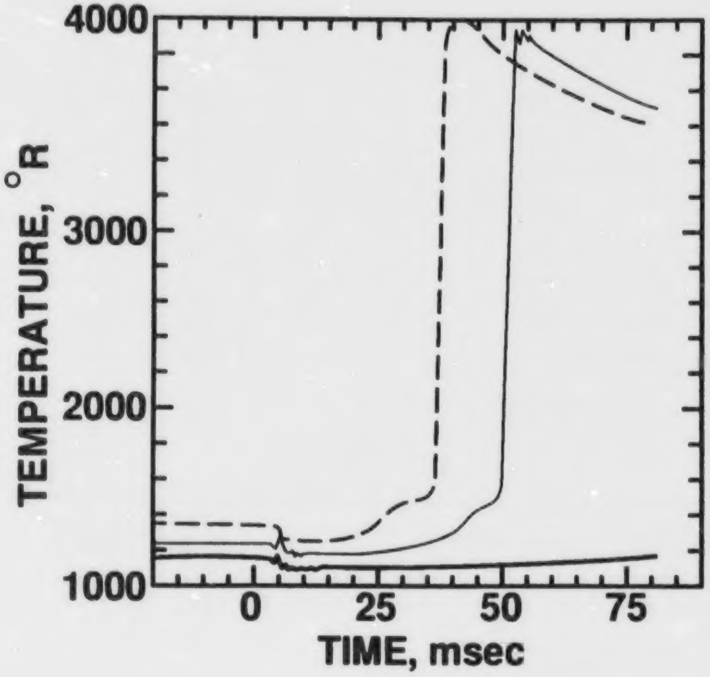
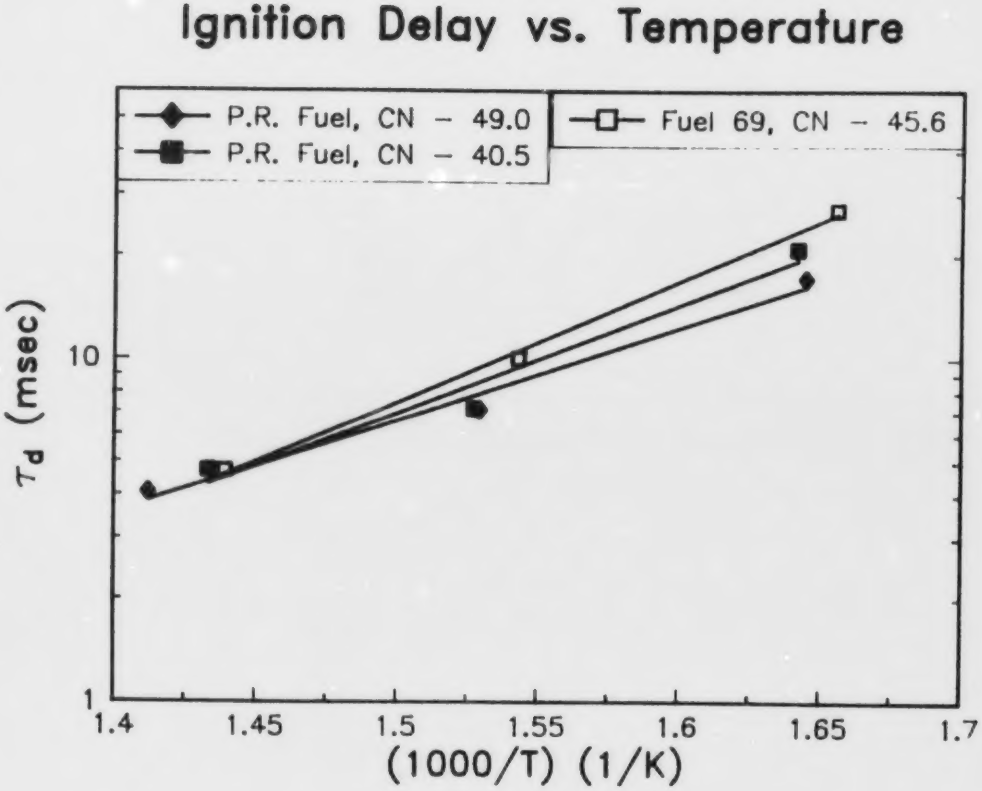


APPARENT ACTIVATION ENERGIES

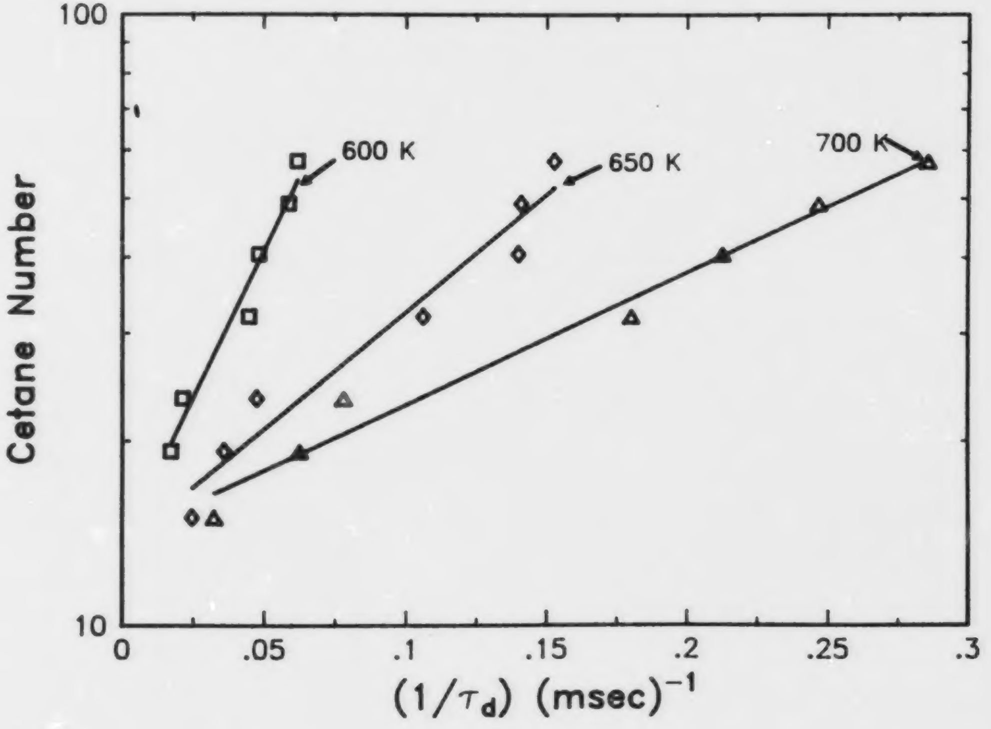
CN	kcal/mole
15	-
19	12.9
24	12.3
32	11.9
41	14.3
49	12.3
58	14.2
100	15.7

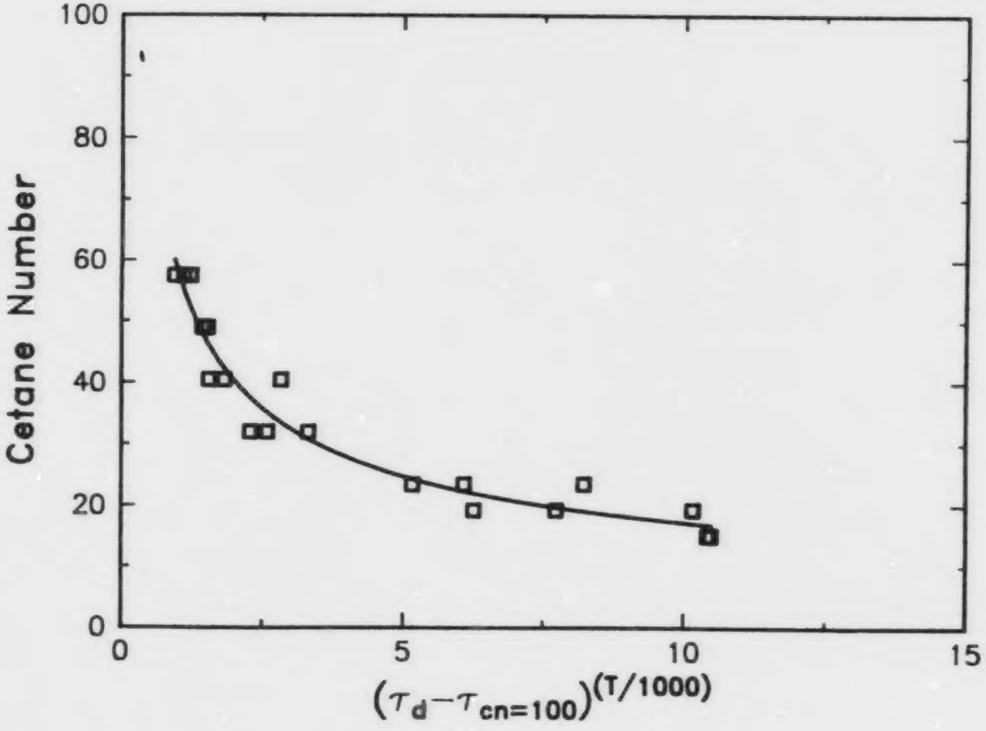
APPARENT ACTIVATION ENERGIES

CN	kcal/mole
46	16.0
44	17.4
49	14.3
42	17.7


Ignition Delay vs. Temperature
P.R. Fuel, CN - 49.0
P.R. Fuel, CN - 40.5
Fuel 69, CN - 45.6
τ_d (msec)
10
1
1.4
1.45
1.5
1.55
1.6
1.65
1.7
(1000/T) (1/K)

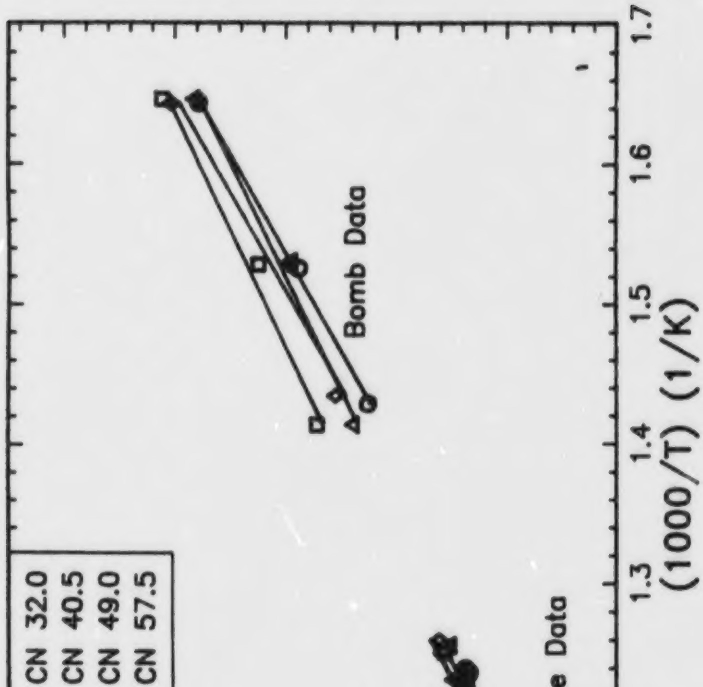
Cetane Number vs Ignition Delay
Delay Based on Heat Release



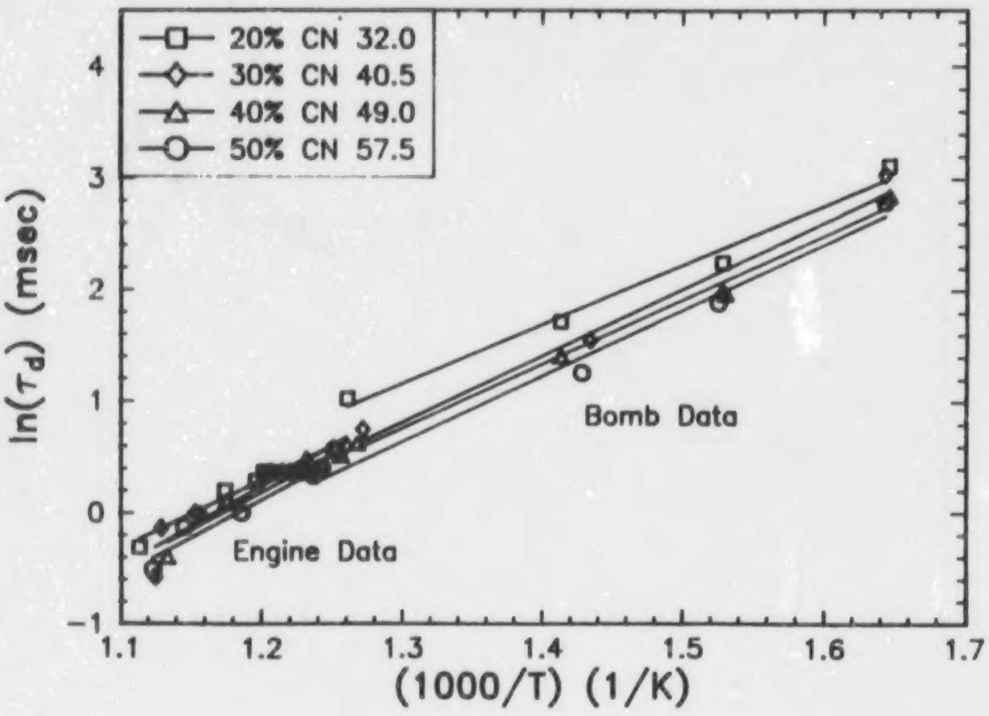


Cetane Number vs Ignition Delay
Delay Based on Heat Release

Ignition Delay vs. Temperature
Delay Based on Heat Release

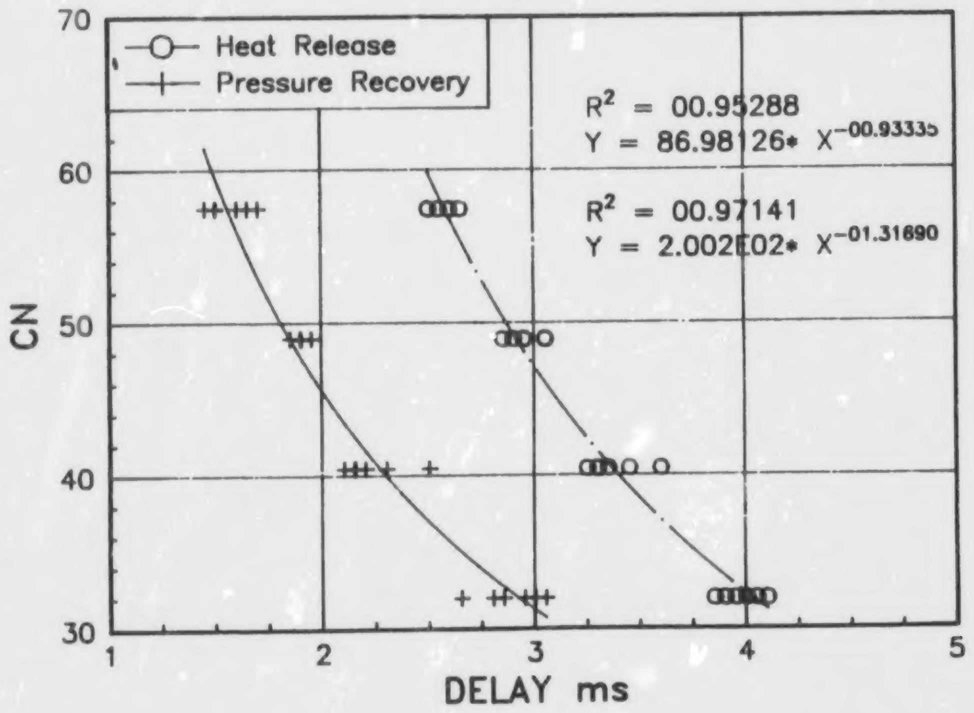


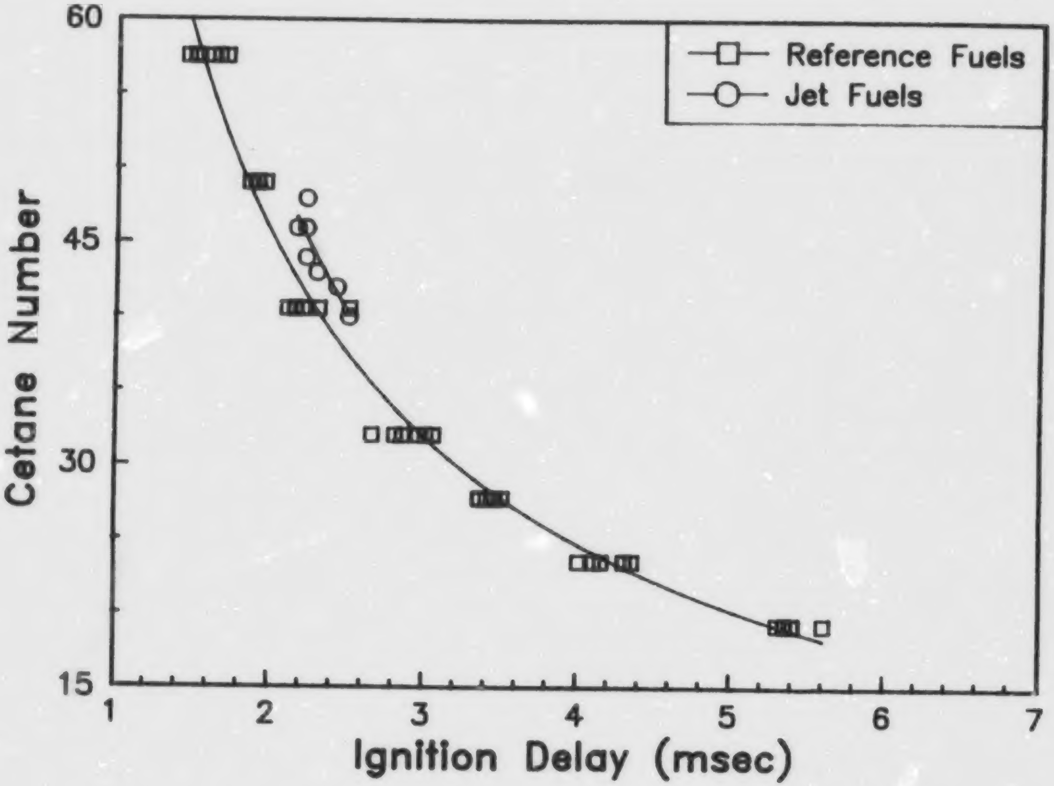
Ignition Delay vs. Temperature
Delay Based on Heat Release



Cetane Number vs. Ignition Delay

Based on Pressure Recovery and Heat Release




Reference Fuels
Jet Fuels
Cetane Number
60
45
30
15
1
2
3
4
5
6
7
Ignition Delay (msec)

$$\tau_d = X_{O2}^{b1} X_{Fuel}^{b2} \rho_{Air}^{b3} \exp(b_4/T)$$

FUTURE

CVCA: 1. RATING UNKNOWN FUELS
2. DELAY=$F(T,P,\rho,O_2)$

ENGINE: DELAY=$F(T,\phi,\rho)$

INFLUENCE OF FUEL SULFUR ON DIESEL PARTICULATE EMISSIONS

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MELROSE PARK, IL 60160

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PRESENTATION TO
FOURTH WINDSOR WORKSHOP
ON ALTERNATIVE FUELS
WINDSOR,ONTARIO
JUNE 20-22,1988

ABSTRACT

An experimental program was conducted to evaluate the contribution of fuel sulfur to brake specific particulate emissions. Three diesel engines-typical for medium and heavy duty truck applications-were tested in four transient cycles of various average loading factors. Three experimental fuels were used having the same basic characteristics, but a sulfur content of 0.05%, 0.19% and 0.29%, respectively.

Analysis of test results concluded that, among the factors investigated, fuel sulfur was the most important factor contributing to brake specific particulate variation. For an increase of 0.1% in fuel sulfur, brake specific particulates increase by about 0.025 g/BHP-hr, due to addition of soluble sulfates and bound water. Combustion system, engine type, cycle loading, particulate makeup, had only a weak contribution to the brake specific sulfate variation.

Conversion rates of fuel sulfur to sulfates on particulates were in the range of one to three percent. These results were computed from actual test results and were confirmed by regression analysis of the experimental data.

PROGRAM OBJECTIVE

- -EVALUATE SULFUR CONTRIBUTION TO DIESEL ENGINE PARTICULATES:
  - -FOR PRODUCTION ENGINES
  - -FOR DEVELOPMENT ENGINES
  - -FOR "BEST EFFORT"/ADVANCED COMBUSTION SYSTEMS
- -ASSESS IMPLICATIONS OF FUEL SULFUR TO THE USE OF CATALYTIC AFTERTREATMENT SYSTEMS (TRAP-OXIDIZERS,CONVERTERS)

-THREE ENGINES TESTED TO DATE

-7.3L IDI 185 BHP @ 3300 RPM

-DTA 466 210 (C) BHP @ 2400 RPM

-DTA 466 215 (F) BHP @ 2400 RPM]

-TEST PROGRAM FOR EACH ENGINE INCLUDES

SEVERAL RUNS OF EACH

-H.D. TRANSIENT TEST (HOT)

-CYCLE SEGMENTS: -NYNF
-LANF
-LAFY

FUEL

-BASELINE LOW SULFUR FUEL (CALIFORNIA)

SULFUR	(% W)	0.049
API GRAVITY		34.6
CETANE INDEX		48.5
AROMATICS	(% V)	26.7

-SULFUR "DOPING " WITH DTBDS TO OBTAIN:

0.19 %
0.29 %

-THREE SULFUR LEVELS:

0.05 % ; 0.19 % ; 0.29 %

TEST ENGINE CHARACTERISTICS

	I	II	III
ENGINE DESIGNATION	7.3 IDI	DTA 466	DTA 466
COMBUSTION SYSTEM	Indirect Injection Ricardo Comet	Direct Injection	Direct Injection
ADMISSION	Naturally Aspirated	Turbo/Air-Air Intercooled	Turbo/Air-Air Intercooled
CONFIGURATION	OHV V-8	Inline 6 Cylinder	Inline 6 Cylinder
RATED POWER (BHP @ RPM)	185 @ 3300	210(C) @ 2400	210(F) @ 2400
BORE x STROKE (In.)	4.11 x 4.8	4.30 x 5.35	4.30 x 5.35
DISPLACEMENT (Liter/Cu. In.)	7.3/444	7.6/466	7.6/466
COMPRESSION RATIO	21.8: 1	16.3: 1	16.3: 1
EMISS. (HD TRANSIENT CYCLE) NOx/HC/PT (g/bhp-h)	3.63/.58/.32	5.77/.77/.31	8.30/.64/.30

TEST FUEL PROPERTIES

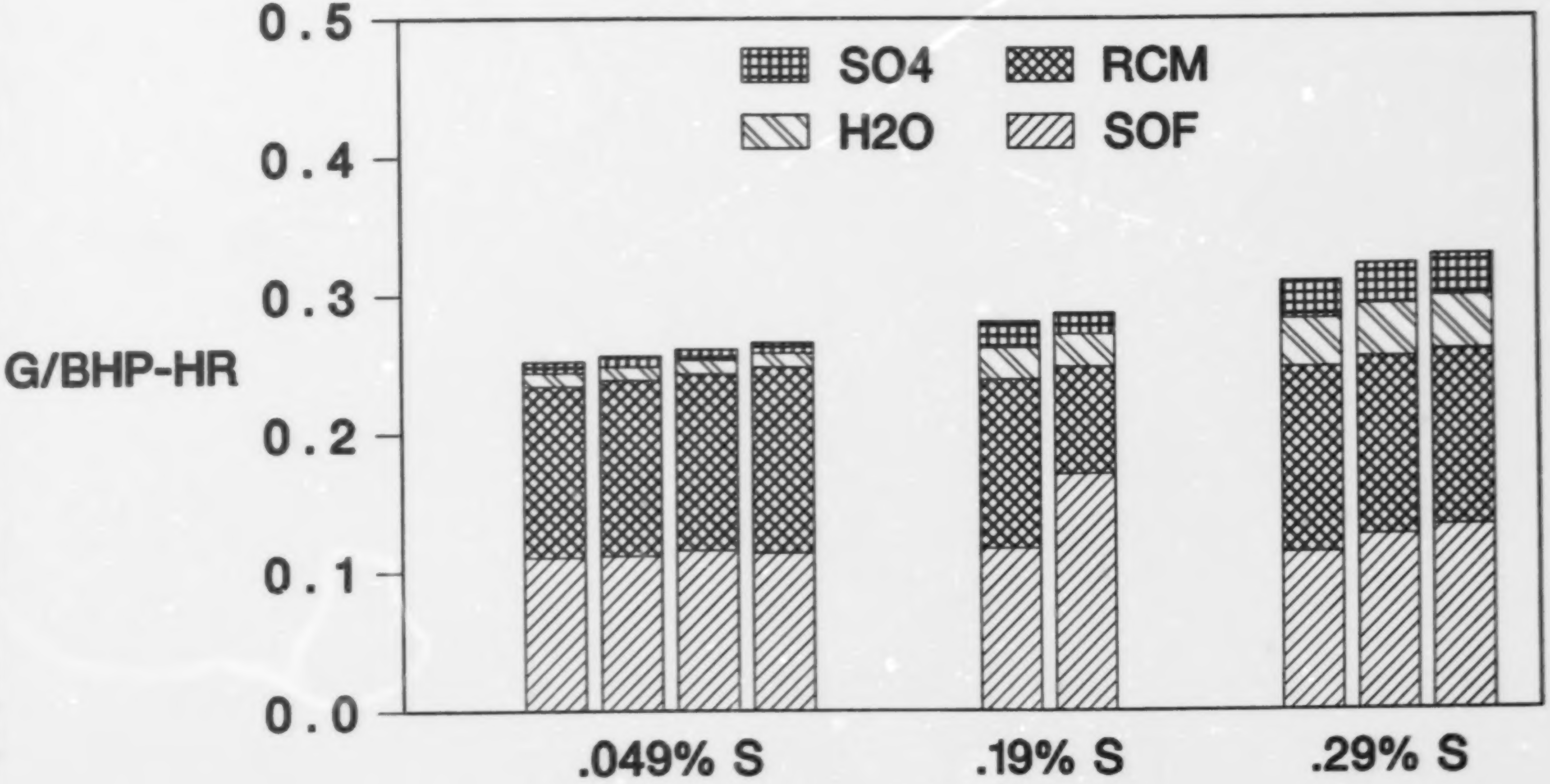
	A	B	C
Sulfur Level (% W)	.05	.19	.29
API Gravity (Deg)	34.6	34.6	34.6
Cetane Index (-)	48.5	48.5	48.5
Aromatics (% V)	26.7	26.7	26.7
Distillation Data (^{O}F)			
- 10%	472	472	472
- 50%	532	532	532
- 90%	591	591	591

TRANSIENT TEST CYCLE CHARACTERISTICS

CYCLE	TYPE	DURATION (Minutes)	LOAD FACTOR (Avg. %)
EPA - Heavy Duty	Transient	20	19
1st Qtr. (NYNF)	Transient	20	9
2nd Qtr. (LANF)	Transient	20	14
3rd Qtr. (LAFY)	Transient	20	44

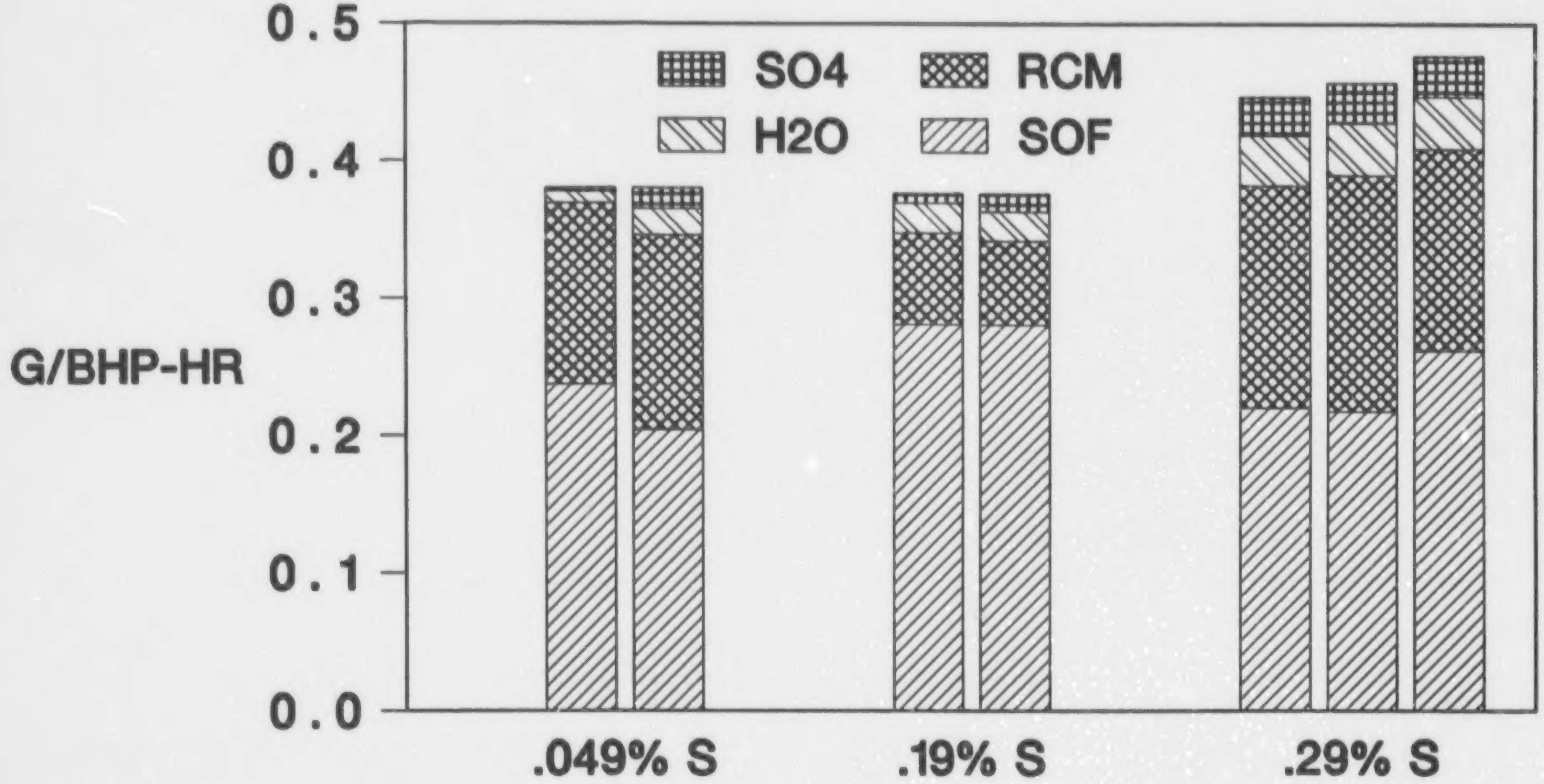
PARTICULATE ANALYSIS - FUEL SULFUR EFFECT

Engine: 7.3L/Z207 - HD Transient Cycle



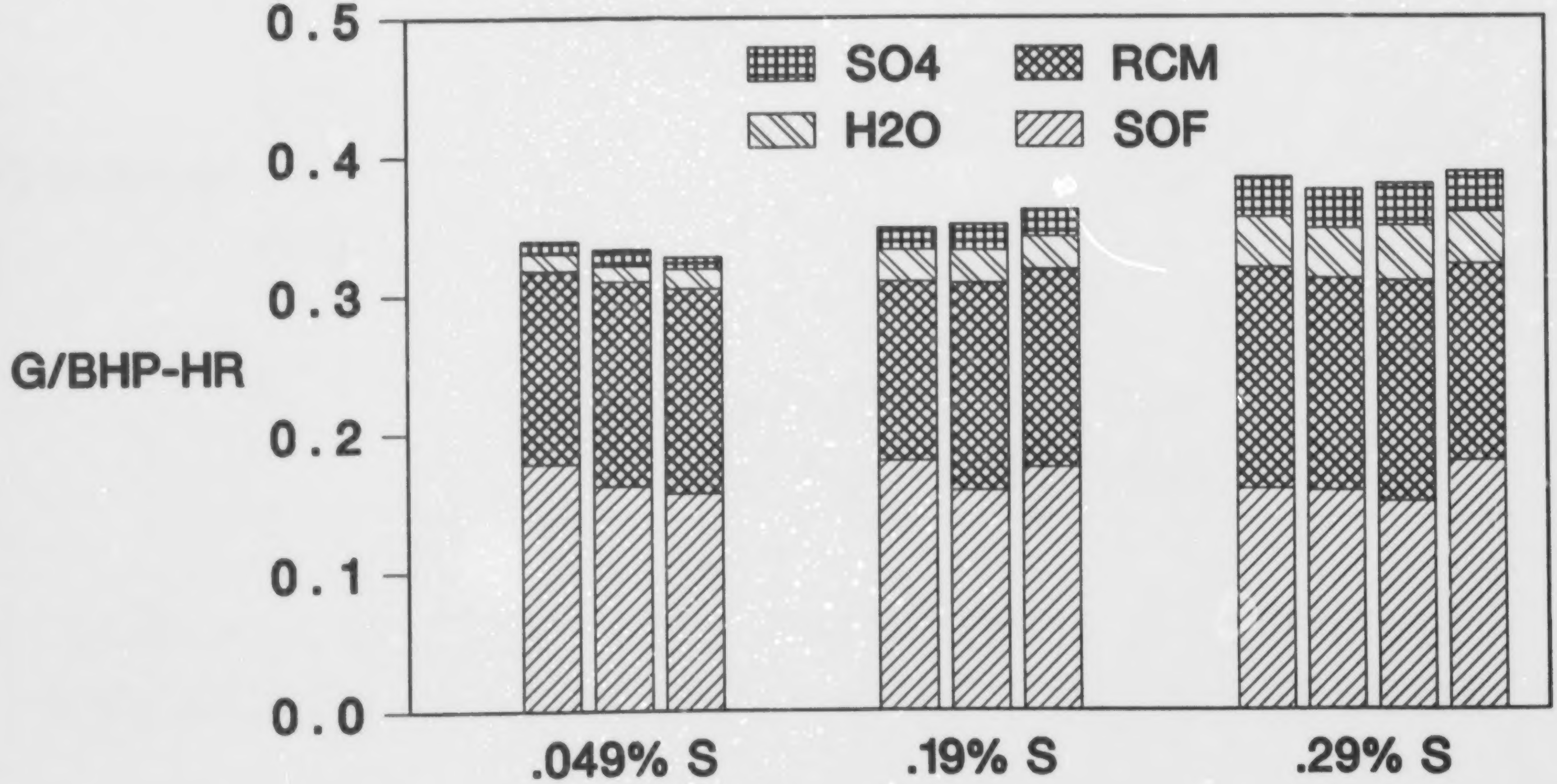
PARTICULATE ANALYSIS - FUEL SULFUR EFFECT

Engine: 7.3L/Z207 - HD Transient Cycle 1st Qtr (NYNF)



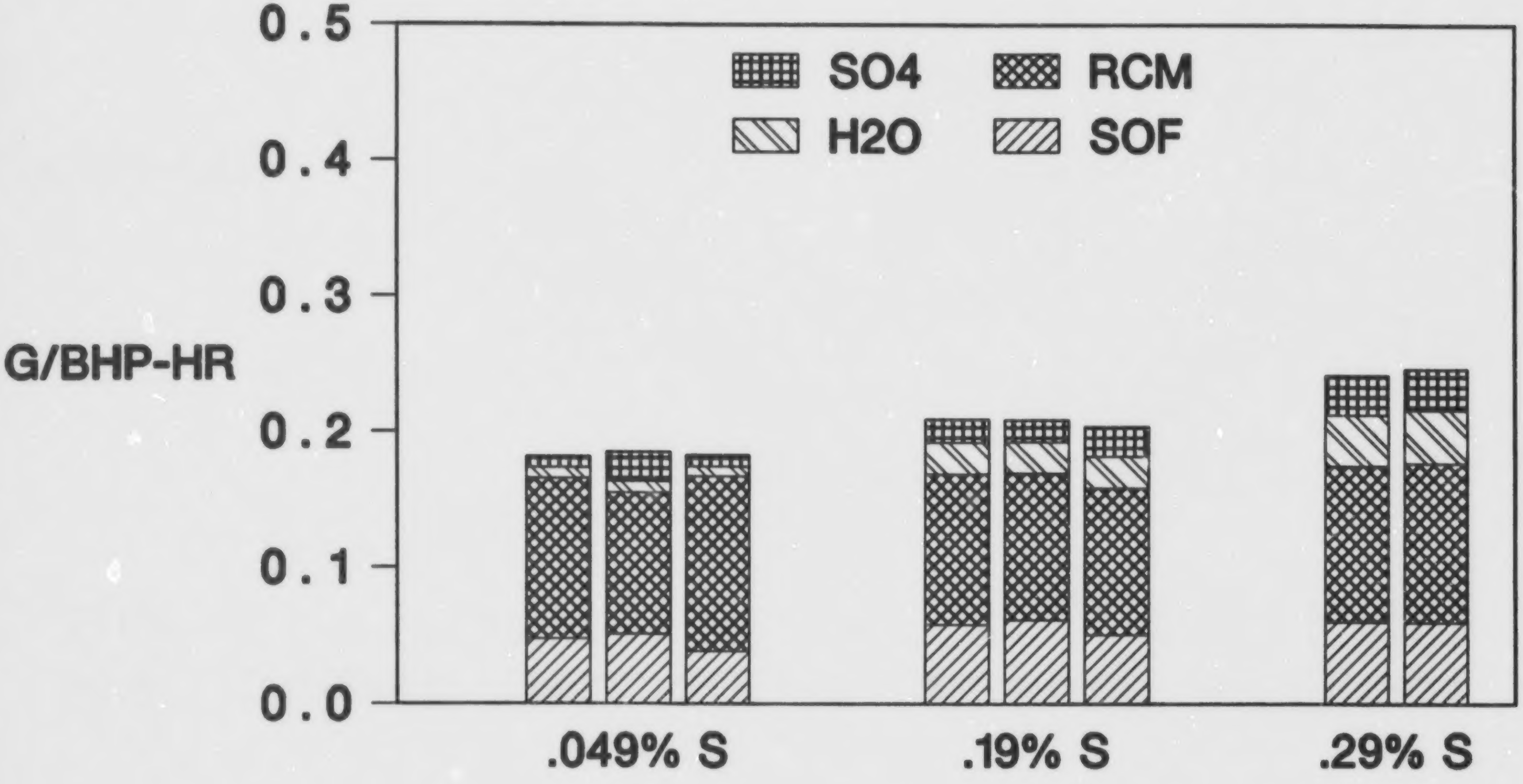
PARTICULATE ANALYSIS - FUEL SULFUR EFFECT

Engine: 7.3L/Z207 - HD Transient Cycle 2nd Qtr (LANF)



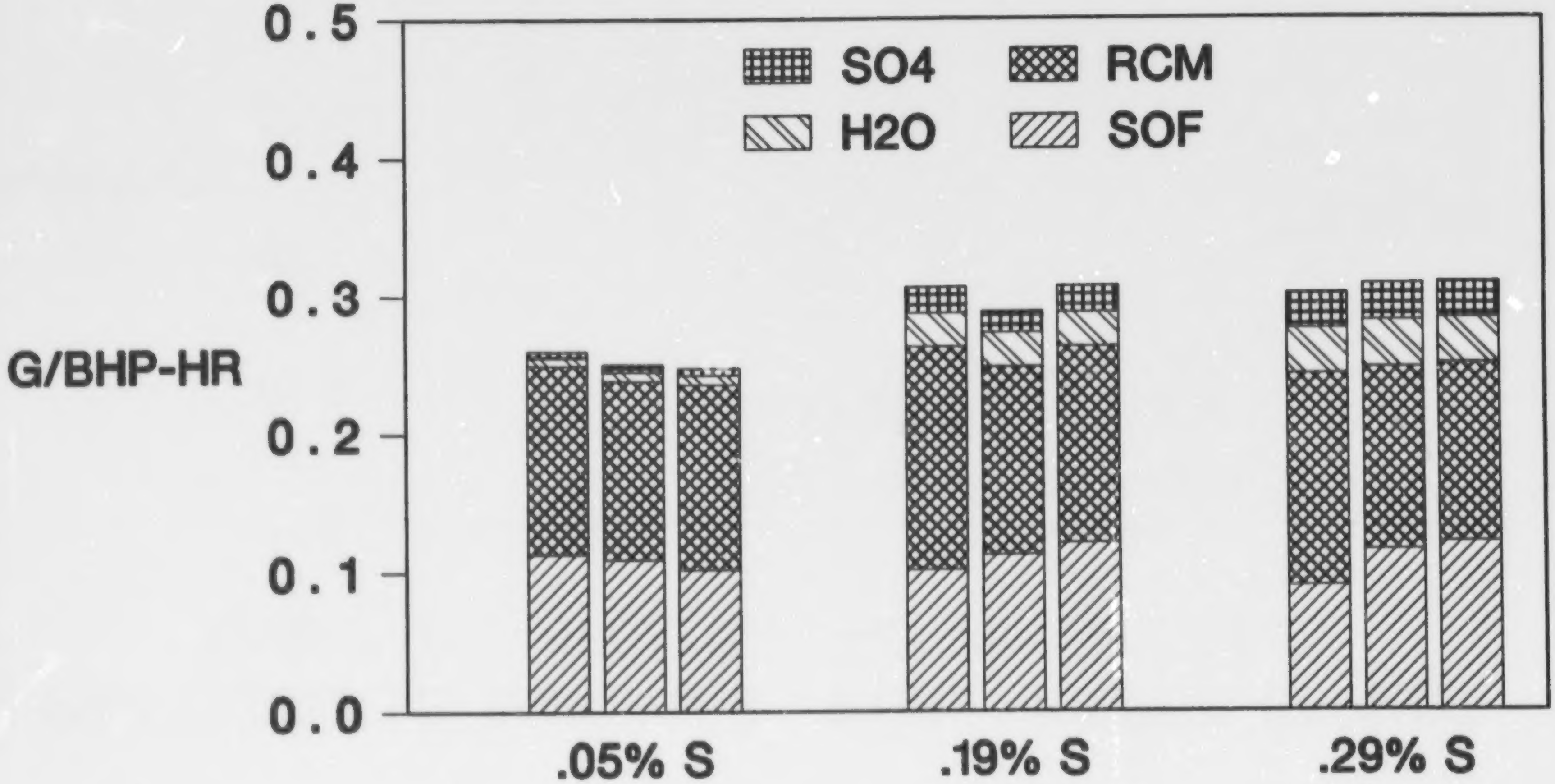
PARTICULATE ANALYSIS - FUEL SULFUR EFFECT

Engine: 7.3L/Z207 - HD Transient Cycle 3rd Qtr (LAF)



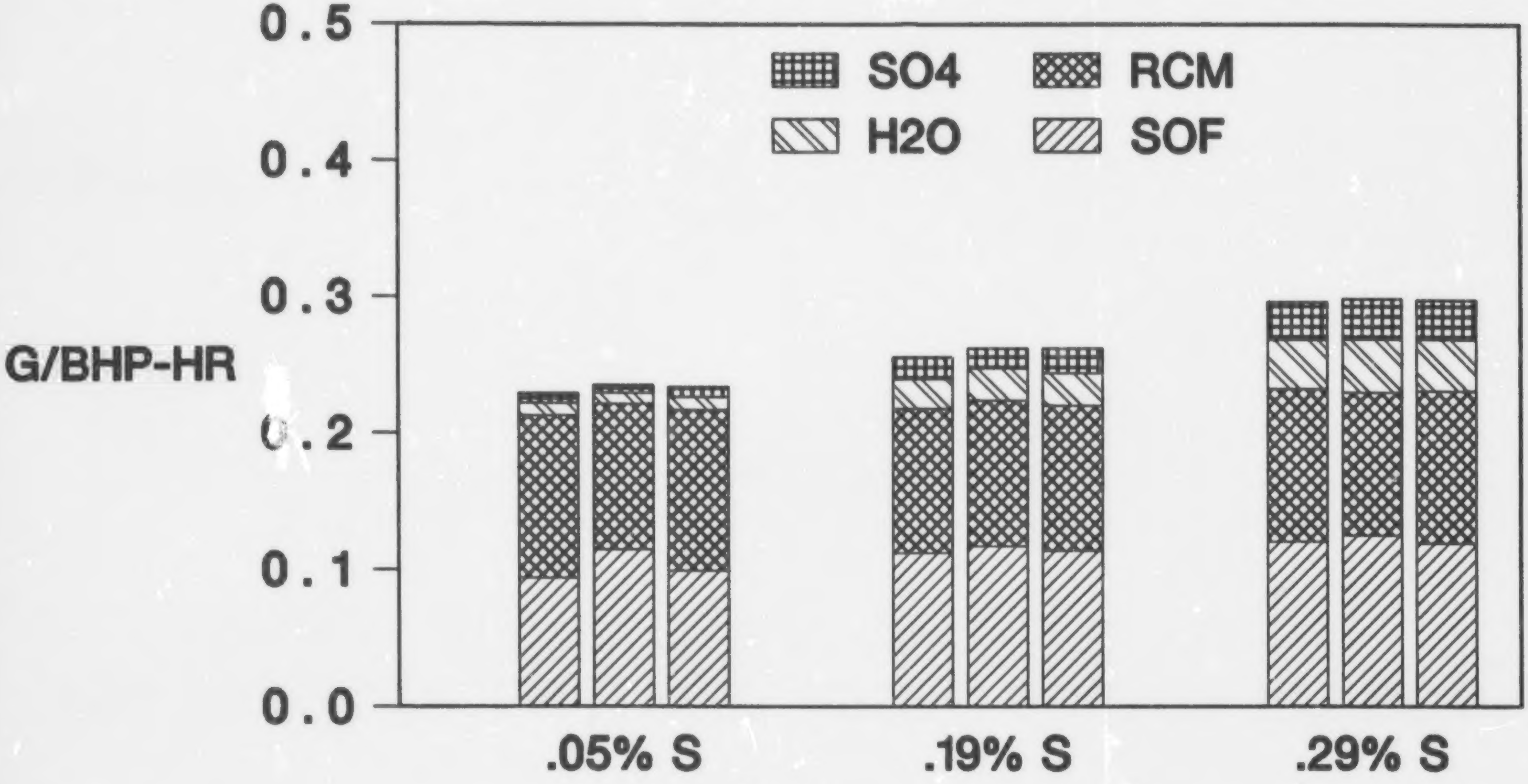
PARTICULATE ANALYSIS - FUEL SULFUR EFFECT

Engine: DTA 466/210C - HD Transient Cycle



PARTICULATE ANALYSIS - FUEL SULFUR EFFECT

Engine: DTA 466/215F - HD Transient Cycle



PARTICULATE COMPOSITION (7.3 IDI)

CYCLE	S %	TPM g/bhp-h	SOF %	RCM %	SO4 %	H20 %
NYNF	0.05	.38	66.0	27.7	3.0	3.9
	0.19	.38	74.0	16.4	4.3	5.7
	0.29	.46	50.7	35.0	6.2	8.1
LANF	0.05	.33	49.7	43.6	2.9	3.8
	0.19	.35	47.3	41.0	5.1	6.6
	0.29	.38	42.3	40.3	7.6	9.8
HD	0.05	.26	43.7	49.5	2.9	3.8
	0.19	.28	59.0	28.2	6.4	8.3
	0.29	.32	38.8	40.6	8.9	11.6
LAFY	0.05	.18	26.5	65.0	3.3	4.4
	0.19	.21	27.4	52.6	8.6	11.4
	0.29	.24	24.6	47.4	12.2	15.8

PARTICULATE COMPOSITION (DTA 466/210C)

CYCLE	S %	TPM g/bhp-h	SOF %	RCM %	SO4 %	H20 %
NYNF	0.05	.38	58.2	38.6	1.4	1.8
	0.19	.44	50.1	40.4	4.1	5.4
	0.29	.44	50.0	37.6	5.4	7.0
LANF	0.05	.34	46.2	50.4	1.5	1.9
	0.19	.40	39.4	49.2	4.9	6.5
	0.29	.40	42.3	41.9	6.9	8.9
HD	0.05	.25	42.9	52.7	1.9	2.5
	0.19	.30	37.3	48.6	6.1	8.0
	0.29	.31	35.6	45.1	8.4	10.9
LAFY	0.05	.18	28.3	66.0	2.5	3.2
	0.19	.23	25.0	56.0	8.3	10.7
	0.29	.26	26.2	47.8	11.3	14.7

PARTICULATE COMPOSITION (DTA 466/215F)

CYCLE	S %	TPM g/bhp-h	SOF %	RCM %	SO4 %	H20 %
NYNF	0.05	.39	56.0	38.3	2.5	3.2
	0.19	.39	58.2	31.6	4.4	5.8
	0.29	.39	53.2	31.6	6.6	8.6
LANF	0.05	.31	46.4	48.5	2.2	2.9
	0.19	.36	44.0	44.5	5.0	6.5
	0.29	.38	39.9	44.3	6.9	8.9
HD	0.05	.23	44.1	49.3	2.9	3.7
	0.19	.26	43.8	40.8	6.7	8.7
	0.29	.30	40.9	36.8	9.7	12.6
LAFY	0.05	.15	33.3	59.5	3.2	4.1
	0.19	.22	34.5	44.6	9.1	11.8
	0.29	.23	32.2	37.9	13.0	16.9

PARTICULATE COMPOSITION (7.3 IDI)

CYCLE	S %	TPM g/bhp-h	SOF g/bhp-h	RCM g/bhp-h	SULFATE (SO4 + H20)
NYNF	0.05	.38	.253	.106	.020
	0.19	.38	.283	.061	.039
	0.29	.46	.233	.160	.066
LANF	0.05	.33	.166	.145	.021
	0.19	.35	.171	.145	.041
	0.29	.38	.161	.154	.065
HD	0.05	.26	.113	.128	.019
	0.19	.28	.166	.079	.043
	0.29	.32	.124	.129	.066
LAFY	0.05	.18	.046	.117	.014
	0.19	.21	.058	.109	.039
	0.29	.24	.059	.116	.066

PARTICULATE COMPOSITION (DTA 466/210C)

CYCLE	S %	TPM g/bhp-h	SOF g/bhp-h	RCM g/bhp-h	SULFATE (SO4 + H20)
NYNF	0.05	.38	.223	.148	.012
	0.19	.44	.219	.179	.044
	0.29	.44	.220	.165	.055
LANF	0.05	.34	.157	.172	.011
	0.19	.40	.158	.196	.046
	0.29	.40	.167	.169	.064
HD	0.05	.25	.110	.133	.011
	0.19	.30	.112	.146	.044
	0.29	.31	.114	.137	.059
LAFY	0.05	.18	.054	.116	.010
	0.19	.23	.064	.126	.043
	0.29	.26	.070	.123	.067

PARTICULATE COMPOSITION (DTA 466/215F)

CYCLE	S %	TPM g/bhp-h	SOF g/bhp-h	RCM g/bhp-h	SULFATE (S04 + H20)
NYNF	0.05	.39	.216	.148	.021
	0.19	.39	.227	.122	.039
	0.29	.39	.206	.122	.060
LANF	0.05	.31	.142	.148	.016
	0.19	.36	.160	.162	.044
	0.29	.38	.152	.168	.060
HD	0.05	.23	.103	.115	.016
	0.19	.26	.114	.106	.041
	0.29	.30	.122	.109	.066
LAFY	0.05	.15	.052	.092	.011
	0.19	.22	.073	.095	.044
	0.29	.23	.075	.089	.069

SULFUR CONVERSION RATES (7.3 IDI)

CYCLE	S %	TPM g/bhp-h	S TO SO4 %
NYNF	0.05	.46	1.7
	0.19	.50	1.1
	0.29	.51	1.1
LANF	0.05	.56	1.6
	0.19	.61	1.1
	0.29	.66	1.6
HD	0.05	.40	1.8
	0.19	.44	1.4
	0.29	.48	1.4
LAFY	0.05	.32	3.0
	0.19	.31	2.7
	0.29	.34	2.7

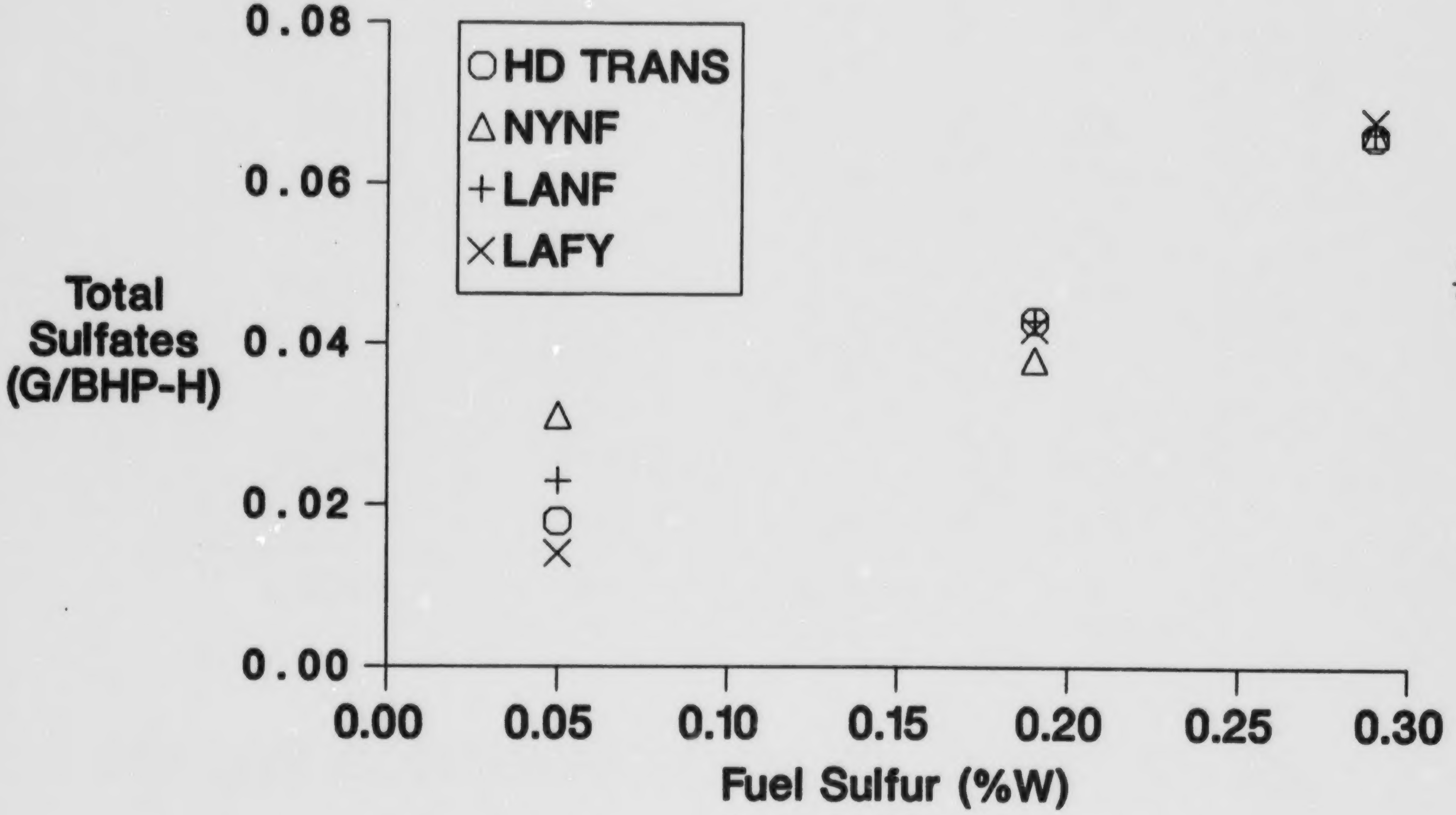
SULFUR CONVERSION RATES (DTA 466/210C)

CYCLE	S %	TPM g/bhp-h	S TO SO4 %
NYNF	0.05	.38	1.6
	0.19	.44	1.4
	0.29	.44	1.2
LANF	0.05	.34	1.6
	0.19	.40	1.7
	0.29	.40	1.5
HD	0.05	.25	1.7
	0.19	.30	1.7
	0.29	.31	1.5
LAFY	0.05	.18	1.6
	0.19	.23	1.8
	0.29	.26	1.8

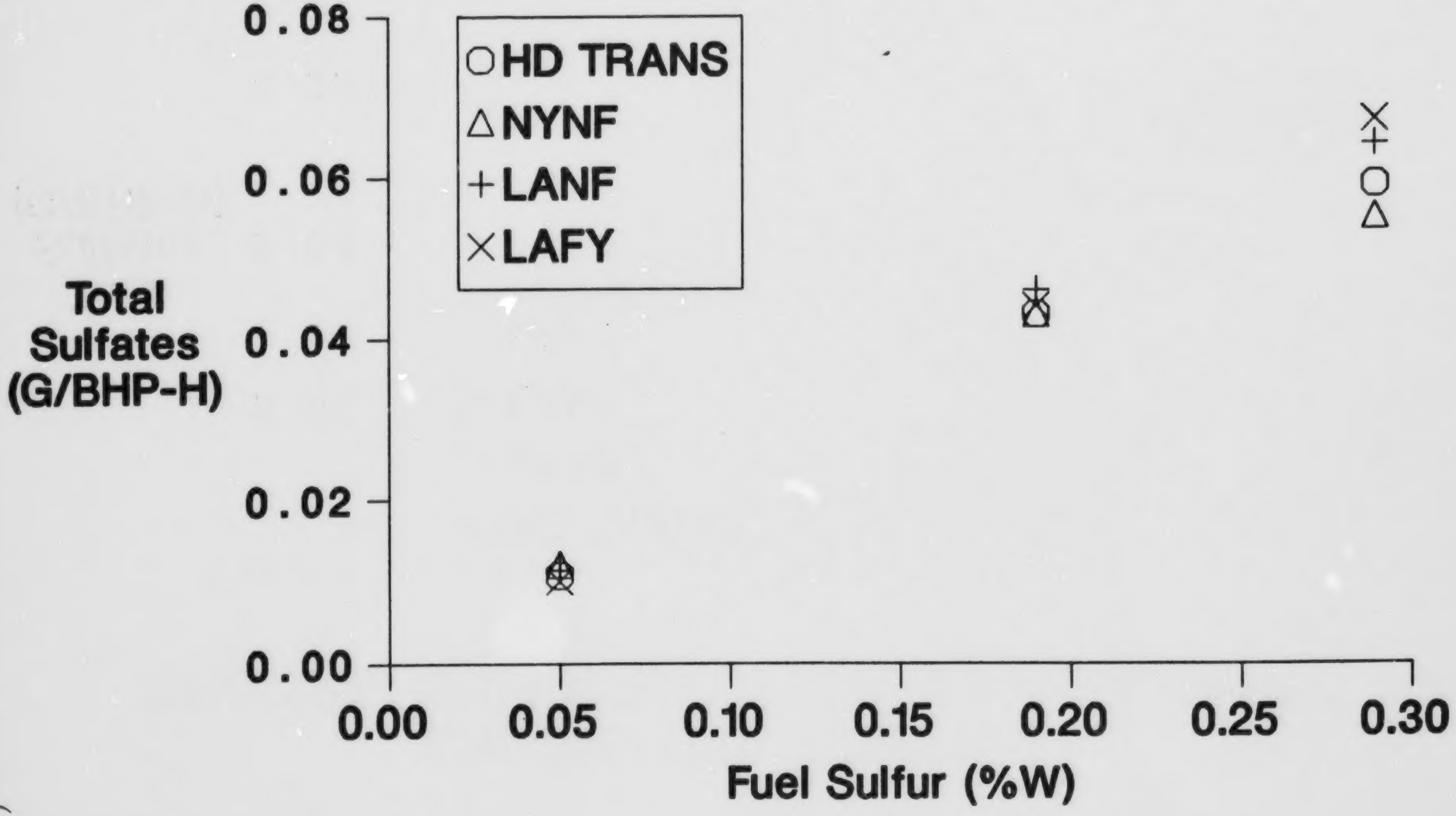
SULFUR CONVERSION RATES (DTA 466/215F)

CYCLE	S %	TPM g/bhp-h	S TO SO4 %
NYNF	0.05	.39	2.9
	0.19	.39	1.4
	0.29	.39	1.4
LANF	0.05	.31	2.2
	0.19	.36	1.6
	0.29	.38	1.5
HD	0.05	.23	2.4
	0.19	.26	1.6
	0.29	.30	1.7
LAFY	0.05	.15	1.9
	0.19	.21	1.9
	0.29	.23	2.0

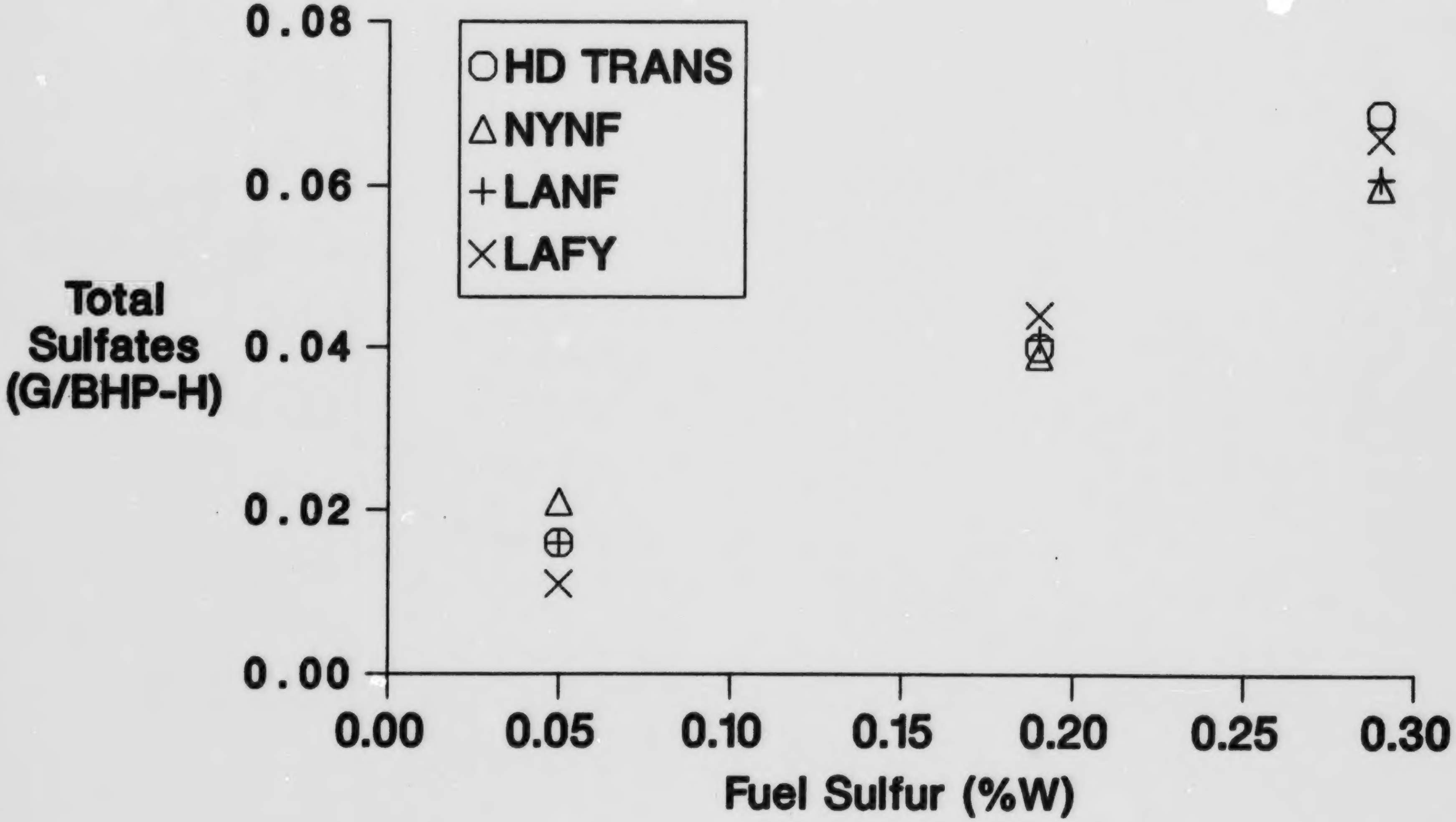
ENGINE: 7.3/IDI
SPECIFIC SULFATE EMISSIONS - SUMMARY



ENGINE: DTA 466/210 C
SPECIFIC SULFATE EMISSIONS - SUMMARY



ENGINE: DTA 466/215 F
SPECIFIC SULFATE EMISSIONS - SUMMARY

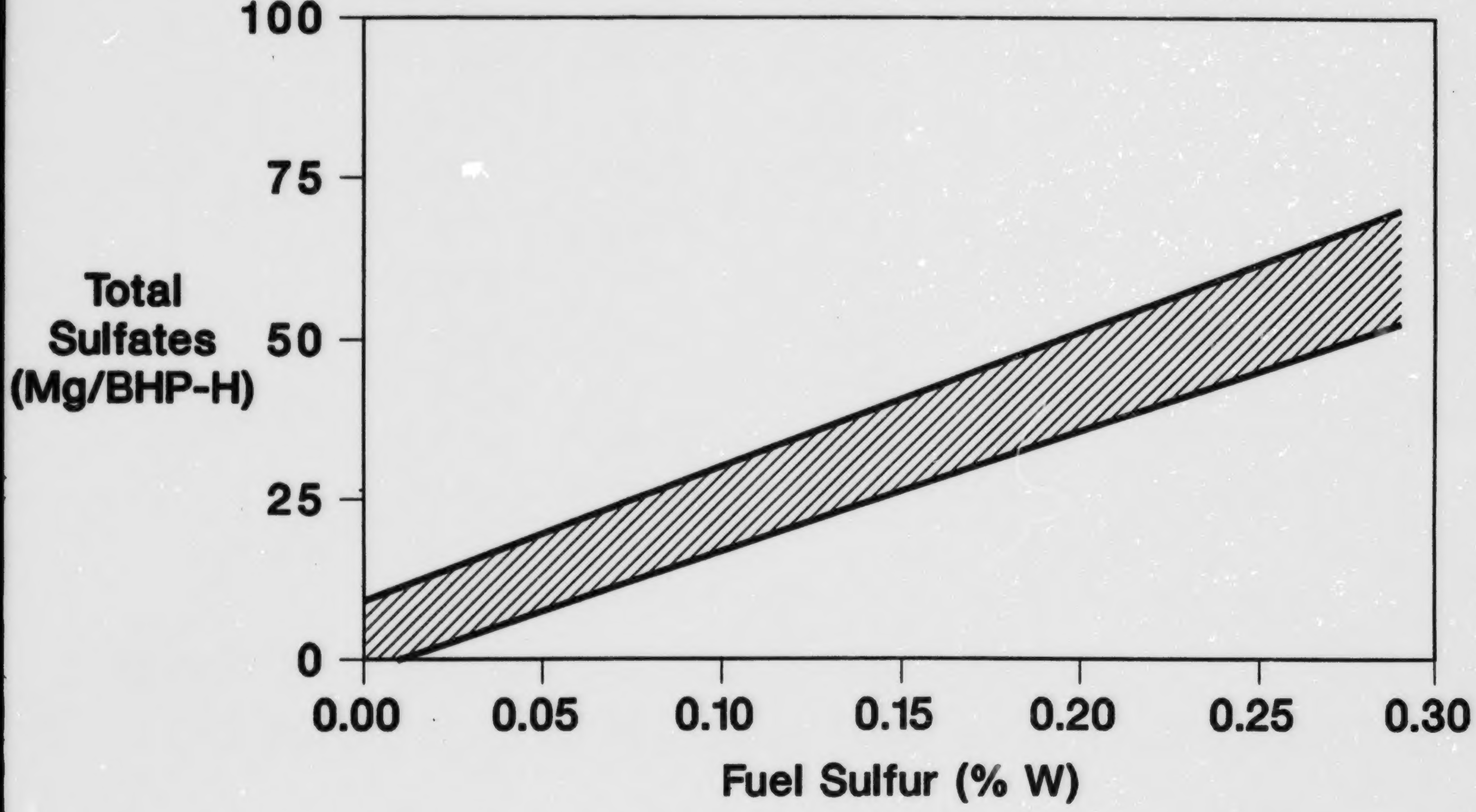


CORRELATION & REGRESSION ANALYSIS COEFFICIENTS
Sulfates & Sulfur For Straight Line Relationship (y=a+bx)

ENGINE	CYCLE	r	r^2	a *	b *
7.3 IDI	NYNF	.9809	.9622	8.44	188.07
	LANF	.9809	.9781	10.40	180.73
	HD	.9965	.9930	8.3[illegible]	194.27
	LAFY	.9930	.9860	1.82	214.22
210C	NYNF	.9840	.9682	4.79	182.34
	LANF	.9962	.9924	0.99	222.71
	HD	.9931	.9862	2.26	202.29
	LAFY	.9999	.9998	-1.94	237.39
215F	NYNF	.9902	.9805	11.68	160.32
	LANF	.9982	.9964	7.42	184.40
	HD	.9954	.9908	4.53	206.42
	LAFY	.9999	.9997	-1.29	241.28

* Units Are: g/bhp-h x 10^{-3}

SULFATE EMISSION REGRESSION ANALYSIS
DOMAIN OF VARIATION - ALL ENGINES



CORRELATION & REGRESSION ANALYSIS DATA
Sulfate & Total Particulates

ENGINE	CYCLE	r	r^2	a	b
7.3 IDI	All	.3588	.1287	13.69	88.50
210C	All	.3165	.1002	12.37	80.79
215F	All	.2793	.0780	19.50	70.07

SUMMARY AND CONCLUSIONS

NAVISTAR'S TEST PROGRAM TO EVALUATE FUEL SULFUR CONTRIBUTION TO PARTICULATE EMISSIONS HAS INVESTIGATED TO DATE :

-TWO COMBUSTION SYSTEMS:

IDI , NATURALLY ASPIRATED
DI , TURBOCHARGED AND AFTERCOOLED
    TWO NOX LEVELS

-FOUR LOADING CYCLES:

H.D. TRANSIENT
NYNF
LANF
LAFY

-THREE SULFUR LEVELS:

0.05 %
0.19 %
0.29 %

THE WORK RESULTED IN THE FOLLOWING CONCLUSIONS:

SUMMARY AND CONCLUSIONS (CONT'D)

1.- REDUCTION OF SULFUR LEVEL IN THE FUEL WAS THE MOST IMPORTANT FACTOR CONTRIBUTING TO PARTICULATE REDUCTION (ABOUT 0.06 TO 0.08 G/BHP-H FOR A REDUCTION OF SULFUR FROM 0.29% to 0.05% - FOR ALL THREE ENGINES AND ALL CYCLES)

2.- COMBUSTION SYSTEM, TURBOCHARGING, EMISSION LEVELS WERE NOT SIGNIFICANT FACTORS IN CONTRIBUTION OF SULFATES TO PARTICULATES. ALL THE SYSTEMS PRODUCED SIMILAR SULFATE EMISSIONS AT THE SAME SULFUR LEVEL IN THE FUEL.

3.- SULFATE EMISSION RATES - IN G/H - INCREASED WITH CYCLE LOADING; THE LAFY SEGMENT OF THE CYCLE PRODUCES MORE SULFATES THAN THE H.D. CYCLE, LANF, ETC.. IN THIS RESPECT, THE H.D. TRANSIENT CYCLE UNDERESTIMATES THE PARTICULATE AND SULFATE EMISSIONS IN THE "REAL WORLD" HIGH - LOAD DRIVING CONDITIONS.

4.- SULFUR CONVERSION RATES (S IN FUEL TO S IN SULFATES) WERE ONE TO THREE PERCENT; NO SIGNIFICANT CHANGE IN CONVERSION RATES WAS FOUND AT LOW SULFUR LEVELS.

5.- FUEL SULFUR DID NOT CHANGE THE AMOUNT OF SOLUBLE ORGANIC FRACTION OR RESIDUAL CARBONACEOUS MATERIAL IN PARTICULATES.

CONCLUSION (CONT'D)

6.- IF SULFUR CONTENT OF DIESEL FUELS IS LOWERED FROM CURRENT LEVELS OF .25% AND .30% TO .05%. NAVISTAR BELIEVES IT CAN ACHIEVE THE 1991 EPA STANDARDS WITHOUT CATALYTIC CONVERTERS OR PARTICULATE TRAPS THROUGH COMBUSTION OPTIMIZATION AND FUEL CONTROL.

7.- IF CATALYTIC CONVERTERS ARE REQUIRED, REMOVAL OF FUEL SULFUR IS STILL NEEDED TO FORESTALL INCREASED SULFATE EMISSIONS AND PREVENT CONVERTER FAILURE DUE TO SULFATE POISONING.

CUMMINS DIRECTION TOWARDS MEETING THE 1991-1994 EMISSION STANDARDS

SHIRISH A SHIMPI

CUMMINS ENGINE COMPANY

TECHNOLOGICAL RESPONSE TO LOW EMISSION REQUIREMENTS -- ENGINE DEVELOPMENT

- DIESEL COMBUSTION BASICS
- ENGINE DEVELOPMENT FOR LOW EMISSIONS
- FUEL EFFECTS ON DIESEL EMISSIONS
- COST OF MEETING EMISSION REQUIREMENTS

DIESEL COMBUSTION BASICS

ENGINE DEVELOPMENT FOR LOW EMISSIONS

- IN-CYLINDER CONTROL
- EXHAUST AFTERTREATMENT

CURRENT STATUS OF ENGINE TECHNOLOGY

- IN-CYLINDER CONTROL CAPABLE OF REACHING PARTICULATE STANDARD LIMITS WITH CURRENT CERT FUEL

- IN-CYLINDER CONTROL NOT CAPABLE OF MEETING DESIGN TARGETS/PRODUCTION COMPLIANCE WITH CURRENT CERT FUEL

- EXHAUST AFTERTREATMENT NOT AVAILABLE FOR 1991 ENGINES
  - COMPLEX TRAP SYSTEMS NOT YET COMMERCIALLY VIABLE
  - CATALYTIC CONVERTERS NOT FEASIBLE WITHOUT LOW-SULFUR FUEL

FUEL EFFECTS ON DIESEL EMISSIONS

- EXHAUST COMPONENTS
  - TOTAL PARTICULATE
  - PAH
  - NOX
- SECONDARY PARTICULATE
  - SULFATE
- FUEL PROPERTIES
  - SULFUR
  - AROMATICS
  - VOLATILITY

PARTICULATE SENSITIVITY TO FUEL SULFUR CONTENT

- SULFUR CONVERSION RATE TO PARTICULATE
- LINEARITY (CONSTANT CONVERSION RATE) TO LOW SULFUR LEVELS

FUEL SULFUR CONVERSION RATE TO PARTICULATE

DIRECT PARTICULATE EMISSIONS

- ENGINE CONVERSION RATE
    - LITERATURE: 1-6% RANGE
        - 3% TYPICAL HISTORICALLY
        - 1.3-3.5% MORE RECENTLY
    - NO INCREASE AT LOW SULFUR LEVELS
- TRAP CONVERSION RATE
    - UP TO 50% WITH CATALYST
    - ??? POSSIBLE IN 1994 TIMEFRAME
- BOUND WATER EFFECT
    - 1.3 GH_2O/GH_2SO_4 AT 50% RELATIVE HUMIDITY

PARTICULATE SENSITIVITY TO FUEL SULFUR CONTENT

EMA SURVEY

- 17 ENGINES
- SULFUR RANGE: 0.35% TO 0.004%
- PARTICULATE RESPONSE: 0.025 G/BHP-HR PER 0.10% SULFUR

GM DATA

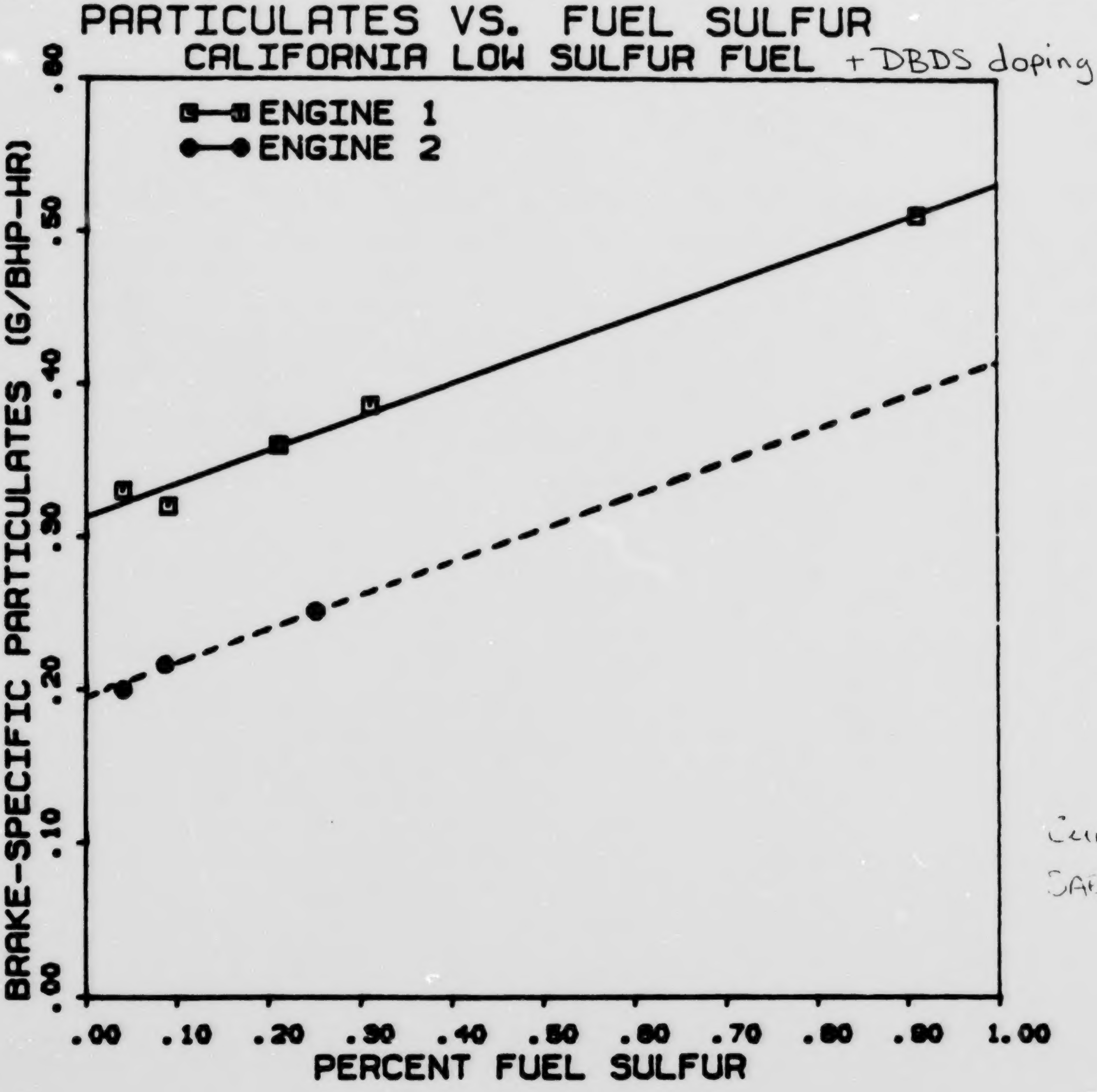
- 12 ENGINES
- SULFUR RANGE: 0.36% TO 0.06%
- PARTICULATE RESPONSE: 0.024 G/BHP-HR PER 0.10% SULFUR

AVERAGE BENEFIT

- 0.054 G/BHP-HR FOR SULFUR REDUCTION FROM 0.27% TO 0.05%

LINEARITY OF PARTICULATE RESPONSE TO SULFUR REDUCTION

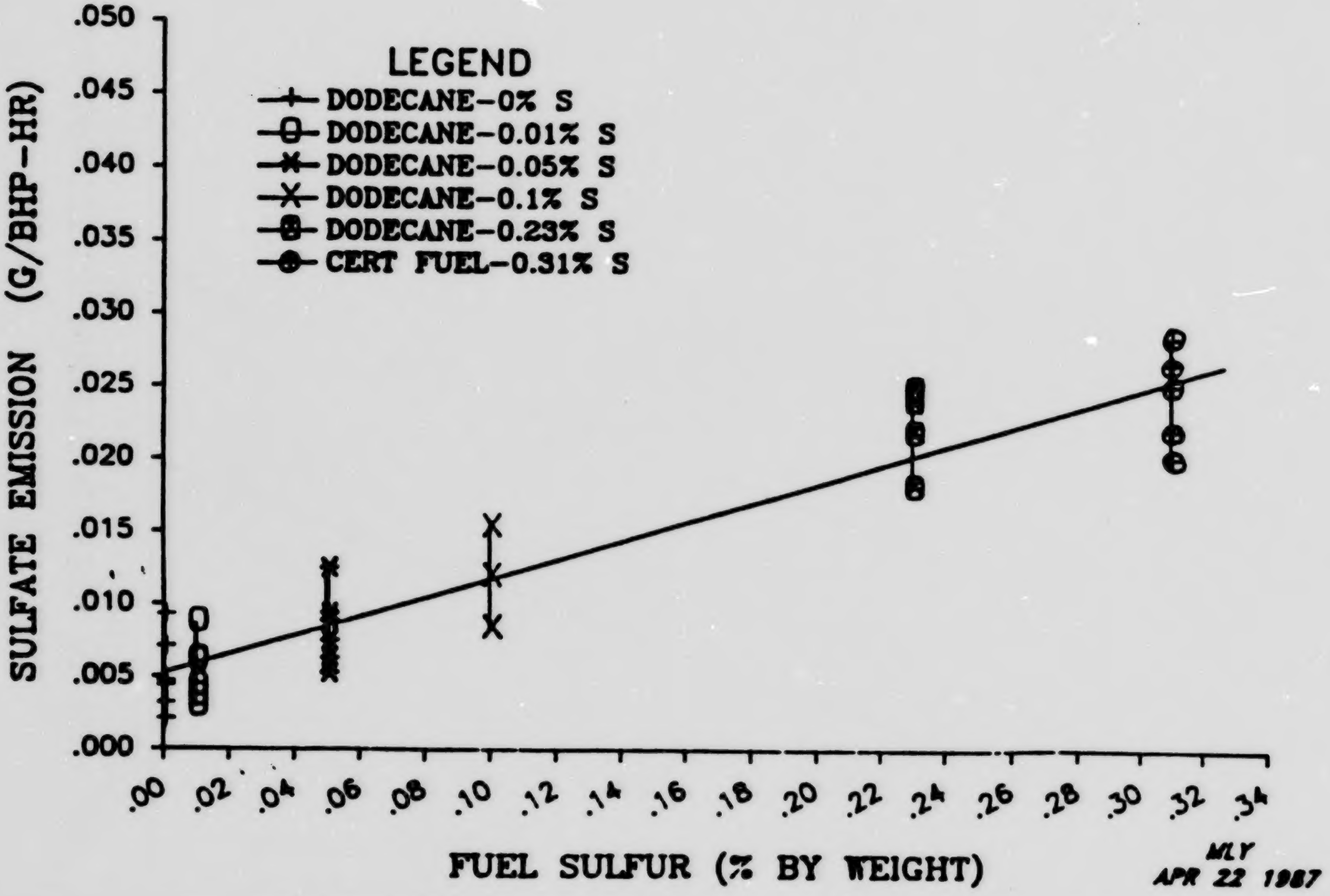
- NON-FUEL SULFATE EMISSIONS (OIL, BACKGROUND) MAKE SULFUR CONVERSION RATE APPEAR TO INCREASE AT LOW SULFUR LEVELS
- CUMMINS EXPERIMENTS USING DODECANE (SAE PAPER 872139) DEMONSTRATED LINEAR RESPONSE OF PARTICULATE TO FUEL SULFUR DOWN TO ZERO SULFUR CONTENT
- CHEVRON EXPERIMENTS (SAE PAPER 841364) DEMONSTRATED LINEAR RESPONSE OF PARTICULATE WHEN FUEL WAS HYDROFINED TO REMOVE SULFUR



PARTICULATES VS. FUEL SULFUR
CALIFORNIA LOW SULFUR FUEL + DBDS doping

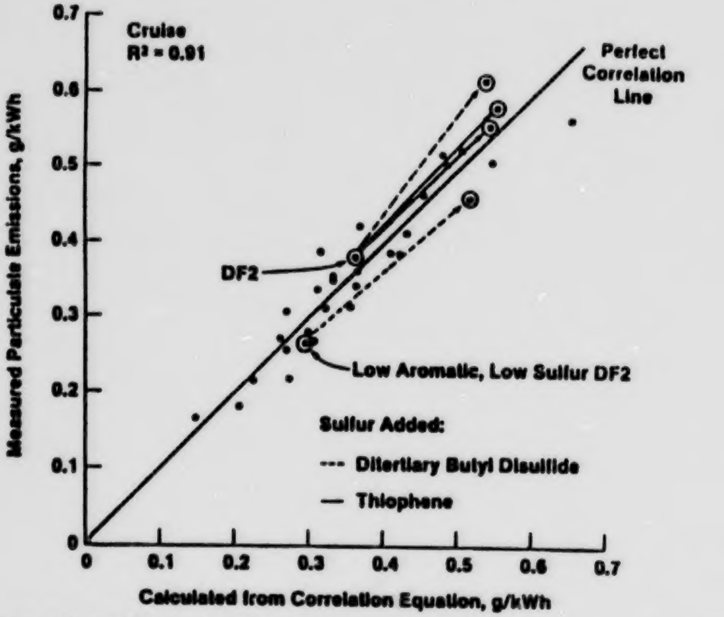
Cummins
SAE 872139

EFFECT OF FUEL SULFUR ON SULFATE EMISSION



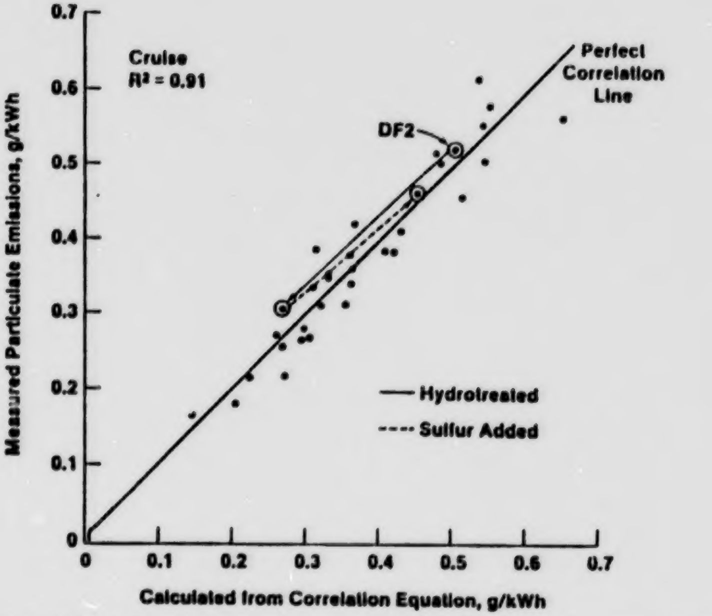
Cummins SAE 872139

level.



$BSP = 1.805 \times 10^{-3} (\% A) + 5.604 \times 10^{-4} (T_{90}, °C) + 5.190 \times 10^{-1} (\% S) + 4.019 \times 10^{-2}$

Fig. 6 - Results of sulfur experiments are illustrated using measured versus calculated BSP for the cruise condition.



$BSP = 1.805 \times 10^{-3} (\% A) + 5.604 \times 10^{-4} (T_{90}, °C) + 5.190 \times 10^{-1} (\% S) + 4.019 \times 10^{-2}$

Fig. 7 - Results of hydrotreating and sulfur-doping of the hydrotreated product are illustrated using measured versus calculated BSP for the cruise condition.

Hydrotreating - A
performed to de
removal by the c
hydrotreating—
process designe
and nitrogen cc

841364

Fuel Composition Effects on Heavy-Duty Diesel Particulate Emissions

J. C. Wall and S. K. Hoekman

omposition -The
ible V) can be
effect of specific
composition. For
sen a base fuel
DF2, having an
of 316°C, and

-111-

FUEL SULFUR CONVERSION RATE TO PARTICULATE

SECONDARY PARTICULATE

- SO_2 CONVERTED TO $(NH_4)_2 SO_4 \cdot H_2O$ IN THE ATMOSPHERE
  - 25-75% RANGE
  - 50% TYPICAL FOR CALCULATIONS
- VISIBILITY IMPAIRMENT SIMILAR IN MAGNITUDE TO CARBONACEOUS PARTICULATE

CONTRIBUTION OF SULFUR-DERIVED PARTICULATE TO TOTAL PARTICULATE MASS

FUEL SULFUR %	CONVERSION RATE %	SULFATE* G/BHP-HR	BOUND WATER G/BHP-HR	TOTAL PARTICULATE G/BHP-HR
0.3	3.0	0.042	0.056	0.098
0.3	1.5	0.021	0.028	0.049
0.05	3.0	0.007	0.009	0.016
0.05	1.5	0.0035	0.0045	0.008
0.03	3.0	0.0042	0.0056	0.010
0.03	1.5	0.0021	0.0028	0.005
0.05	50.	0.117	0.152	0.269
0.05	20.	0.047	0.060	0.107
0.03	50.	0.070	0.091	0.161
0.03	20.	0.028	0.036	0.064
0.50	3.0	0.070	0.091	0.161

*0.4 LB/BHP-HR FUEL CONSUMPTION

PARTICULATE SENSITIVITY TO FUEL AROMATICS CONTENT

- TOTAL PARTICULATE
    - LIGHT DUTY

      GM
      CRC CAPE-32

    - HEAVY DUTY

      CHEVRON
      CATERPILLAR-MOBIL
      CRC VE-1
      CUMMINS

- POLYNUCLEAR AROMATIC HYDROCARBON
    - LIGHT DUTY

      CRC CAPE-32

    - HEAVY DUTY

      CHEVRON
      CATERPILLAR-MOBIL

PARTICULATE SENSITIVITY TO FUEL AROMATICS CONTENT

TOTAL PARTICULATE

LIGHT DUTY

% PARTICULATE REDUCTION PER 10% AROMATIC REDUCTION

- GM (BURLEY AND ROSEBROCK, SAE PAPER 790923)

OLDSMOBILE 5.7L	5%

(SULFUR CORRELATED WITH AROMATICS)

- CRC CAPE-32 (SAE PAPER 861120)

MERCEDES 240D 2.4L	8%
OLDSMOBILE 5.7L	2%
PEUGEOT 505D 2.3L	12%
VW RABBIT 1.6L	30%

PARTICULATE SENSITIVITY TO FUEL AROMATICS CONTENT

TOTAL PARTICULATE

HEAVY DUTY

% PARTICULATE REDUCTION PER 10% AROMATIC REDUCTION

- CHEVRON (SAE NO. 841364)

NTC-290 STEADY STATE	9% (0.04 G/BHP-HR)

- CATERPILLAR-MOBIL (SAE NO. 852078)

3406B STEADY STATE	3% (0.01 G/BHP-HR)
3406B TRANSIENT	23% (0.11 G/BHP-HR)

- CRC VE-1

NTC-400 TRANSIENT	6% (0.03 G/BHP-HR)
SERIES 60 TRANSIENT	0%

- CUMMINS (SAE NO. 872139)

L10 TRANSIENT	7% (0.02 G/BHP-HR)

NO$_X$ SENSITIVITY TO FUEL AROMATIC CONTENT

HEAVY DUTY

% NO$_X$ REDUCTION PER 10% AROMATIC REDUCTION

CATERPILLAR-MOBIL	
3406B STEADY STATE	7%
3406B TRANSIENT	4%
CRC VE-1	
NTC-400 TRANSIENT	2%
SERIES 60 TRANSIENT	3.5-5%

PARTICULATE EMISSIONS AND HEALTH EFFECTS

- HEALTH EFFECTS ASSOCIATED WITH PAH EMISSIONS
- NON-CATALYTIC TRAPS DO NOT REDUCE PAH IN PROPORTION TO REDUCTION IN TOTAL PARTICULATE
  (N-PAH -- THE "HOT" ONES -- MAY INCREASE)
- PAH INCREASE WITH INCREASING AROMATICS -- ORDERS OF MAGNITUDE ABOVE 35-40% AROMATICS
- INITIAL INDICATIONS ARE THAT CATALYTIC TRAPS OR CATALYTIC CONVERTERS SUBSTANTIALLY REDUCE PAH

PARTICULATE SENSITIVITY TO FUEL AROMATICS CONTENT

POLYNUCLEAR AROMATIC HYDROCARBONS

HEAVY DUTY

- TREMENDOUS INCREASE AT HIGHER AROMATICS LEVEL
  - CATERPILLAR-MOBIL: 35% AROMATICS BREAK-POINT
  - CHEVRON: 40% AROMATICS BREAK-POINT

Caterpillar-Mobil SAE paper 852078

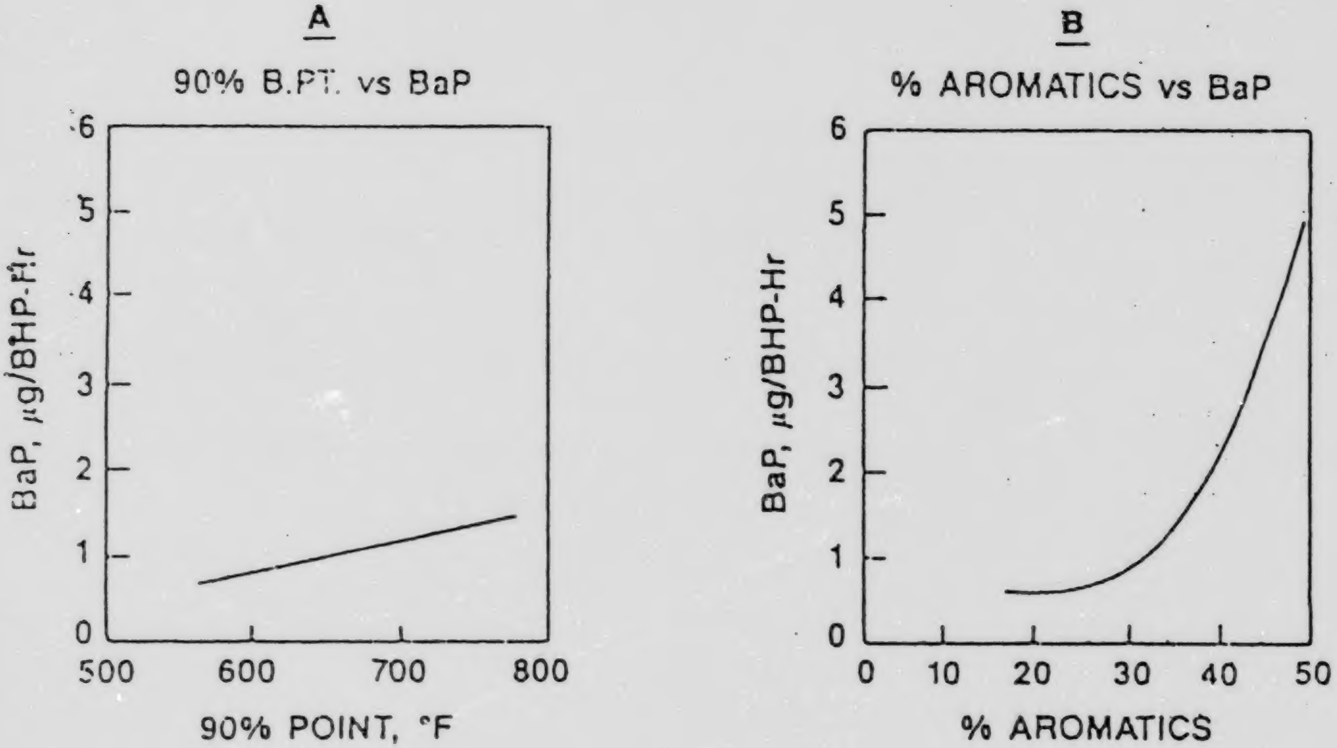
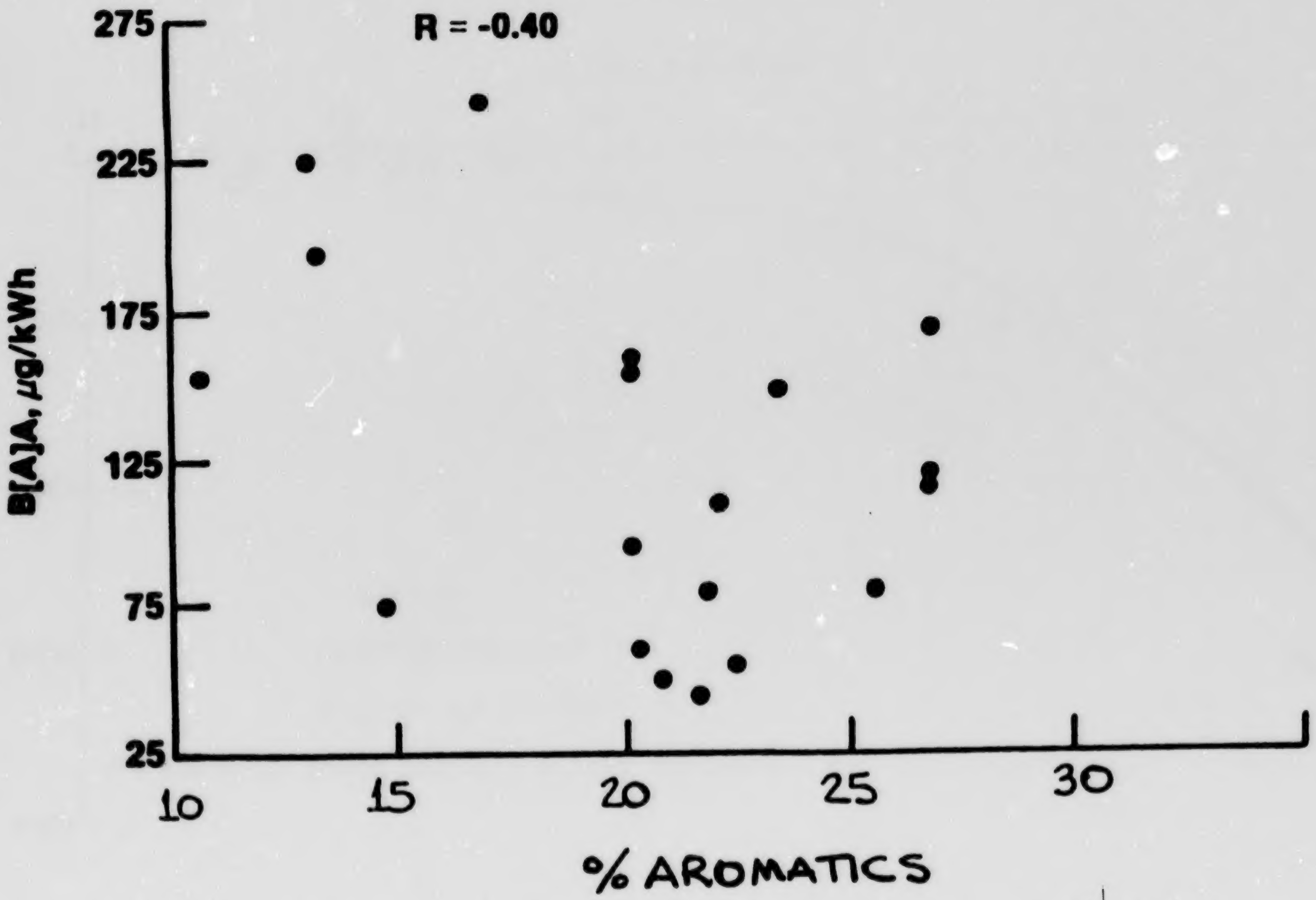


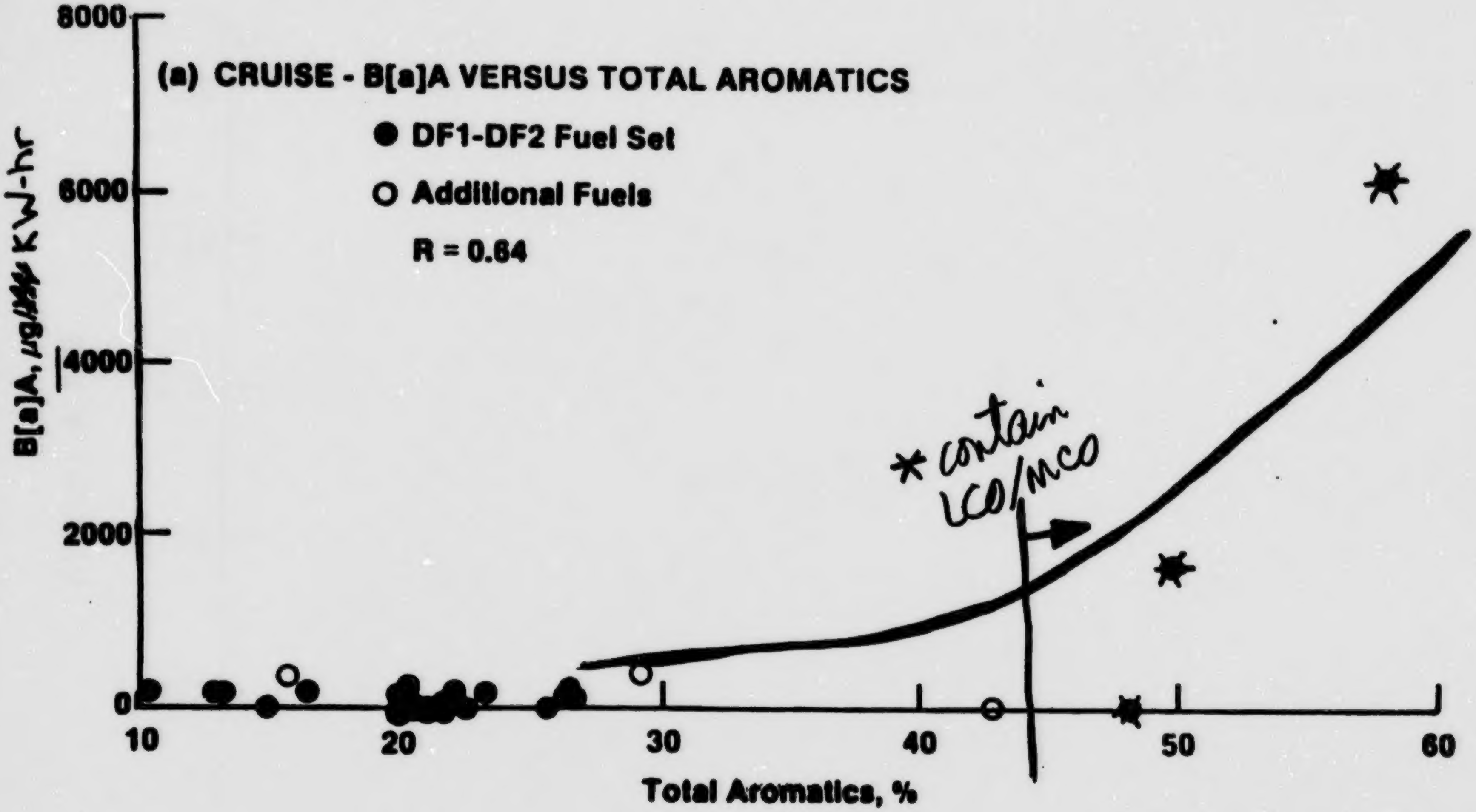
Figure 30

PAH EMISSIONS

(b) CRUISE - B[A]A VERSUS TOTAL AROMATICS



Chevron
SAE 841364



(a) CRUISE - B[a]A VERSUS TOTAL AROMATICS

Chevron
SAE 841364

OTHER FUEL EFFECTS OF DESULFURIZATION

- AROMATICS INCREASE
  - MID-DISTILLATE STREAMS CURRENTLY EXCLUDED FROM DIESEL POOL BECAUSE OF POOR STORAGE STABILITY COULD BE INCLUDED WITH HYDROFINING
    - HIGH AROMATICS STREAMS IN PARTICULAR
    - BIG ECONOMIC INCENTIVE TO DO SO
  - CETANE NUMBER WOULD FALL TO MINIMUM
  - PAH WOULD INCREASE BY ORDERS OF MAGNITUDE

SUMMARY OF FUEL EFFECTS

PARTICULATE

- SULFUR EFFECT ON ENGINE EMISSION (AND NON-CATALYTIC TRAPS)
  - 1.5-3.0% CONVERSION RATE
  - 2.3% CONVERSION RATE (EMA SURVEY)
    - 0.025 G/BHP-HR PER 0.10%S
- SULFUR EFFECT ON CATALYTIC TRAPS
  - 20% CONVERSION RATE - TRANSIENT CYCLE
  - 50% CONVERSION RATE - HIGH LOAD
- AROMATICS EFFECT
  - WIDELY VARIABLE RESPONSE
  - GENERALLY 5-10% PARTICULATE REDUCTION FOR 10% REDUCTION IN AROMATICS

NO_X

- AROMATICS EFFECT
  - 2-5% REDUCTION FOR 10% REDUCTION IN AROMATICS

PAH

- AROMATICS EFFECT
  - BREAK-POINT AT 35-40% AROMATICS

COST OF MEETING EMISSION REQUIREMENTS

- INDUSTRY INVESTMENT IN R & E
- EXHAUST AFTERTREATMENT SYSTEM COSTS AND EQUIVALENT FUEL BREAK-EVEN COST

COST OF MEETING EMISSION REQUIREMENTS --
ESTIMATED ENGINE-INDUSTRY EXPENDITURES: 1986-1993

. R&E COSTS DIRECTLY RELATED TO EMISSIONS

14 COMPANIES	TOTAL CUMMINS R&E
$10 MILLION/YEAR (AVERAGE)	IN 1987 WAS
8 YEARS	$174.3 MILLION

$1.1 BILLION R&E

. MANUFACTURING CAPITAL EXPENDITURES DRIVEN BY EMISSIONS

14 COMPANIES
$150 MILLION RETOOLING/NEW MACHINES

$2.1 BILLION MANUFACTURING

. TOTAL R&E + MANUFACTURING: $3.2 BILLION

ENGINE INDUSTRY EXPENDITURES FOR LOW-EMISSION ENGINES ARE COMPARABLE TO PROJECTED OIL INDUSTRY EXPENDITURES FOR LOW-EMISSION FUELS

COST OF EXHAUST AFTERTREATMENT, AND BREAK-EVEN COST FOR LOW-EMISSION FUEL

- GM (JOHN FISHER LTR TO EMA)
- CATERPILLAR (SAE PAPER 880346)

GM:	VEHICLE LIFETIME	500K MILES 8 YEARS
	INITIAL TRAP COST	$4000
	FUEL CONSUMPTION PENALTY	2%
	TOTAL LIFECYCLE COST	2.27 ¢/MI
	BREAK-EVEN FUEL COST	+14.6 ¢/GAL
CAT:	VEHICLE LIFETIME (WITH RESALE AT END)	290K MILES
	FUEL CONSUMPTION PENALTY	1%

BREAK-EVEN FUEL COST

$2000 TRAP	+20¢/GAL
$4000 TRAP	+23¢/GAL

FUEL MODIFICATION COSTS TO THE CONSUMER ARE WITHIN THE RANGE OF EXHAUST AFTERTREATMENT COSTS FOR LOW EMISSIONS

ENGINE/EXHAUST AFTERTREATMENT TECHNOLOGY

CAN: REDUCE CARBONACEOUS PARTICULATE
REDUCE NO_x
REDUCE PAH

CANNOT: REDUCE SULFATE

OPPORTUNITY FOR JOINT SOLUTION:

- FUEL SULFUR REDUCTION FOR SULFATE CONTROL
- ENGINE DEVELOPMENT FOR CARBONACEOUS PARTICULATE CONTROL
- AROMATICS LIMIT TO PREVENT RUNAWAY PAH FROM UNCONTROLLED ENGINES

DEVELOPMENT OF L10 NG ENGINE

V.K. Duggal
Cummins Engine Company, Inc.

D. Petherick
T. Topaloglu
Ministry of Transportation of Ontario

W. Goetz
Ontario Research Foundation

ACCOMPLISHED TO DATE

- Basic engine conversion completed
- Turbocharging with charge air cooling (low flow cooling system)
- IMPCO fuel system components
- Solid state ignition system
- Electronic governor
- Engine performance meeting targets
- 13 mode emission tests

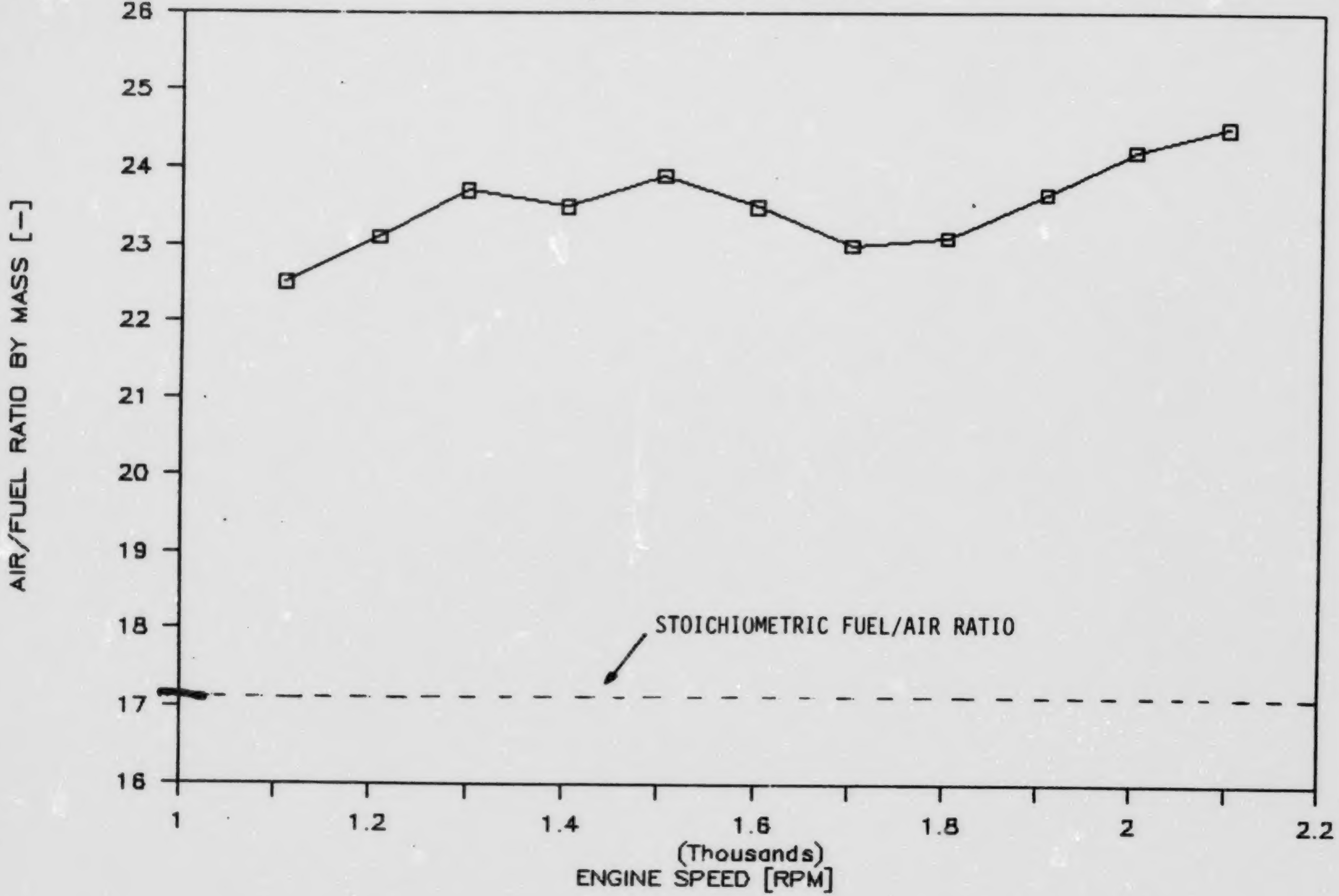
TARGETS

- 240 HP @ 2100 RPM
- 750 FTLB torque @ 1100 RPM
- Lean fast burn technology for NO_x control
- Durability same as diesel or better

OBJECTIVES

Develop heavy-duty natural gas engine for 1991 bus application

Preliminary Performance and Emissions Results

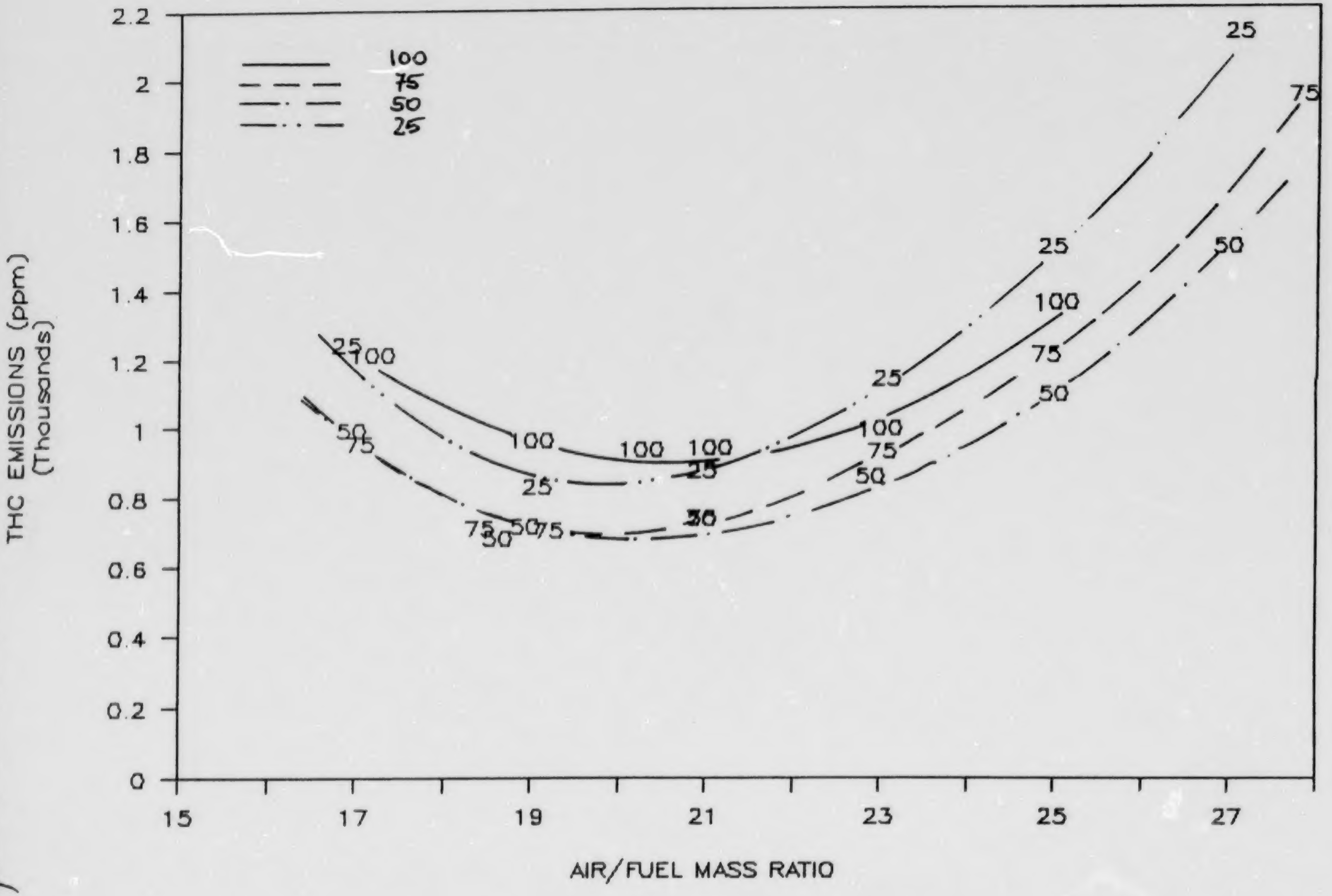


L10 NG ENGINE — WOT PERFORMANCE

AIR/FUEL RATIO vs. SPEED

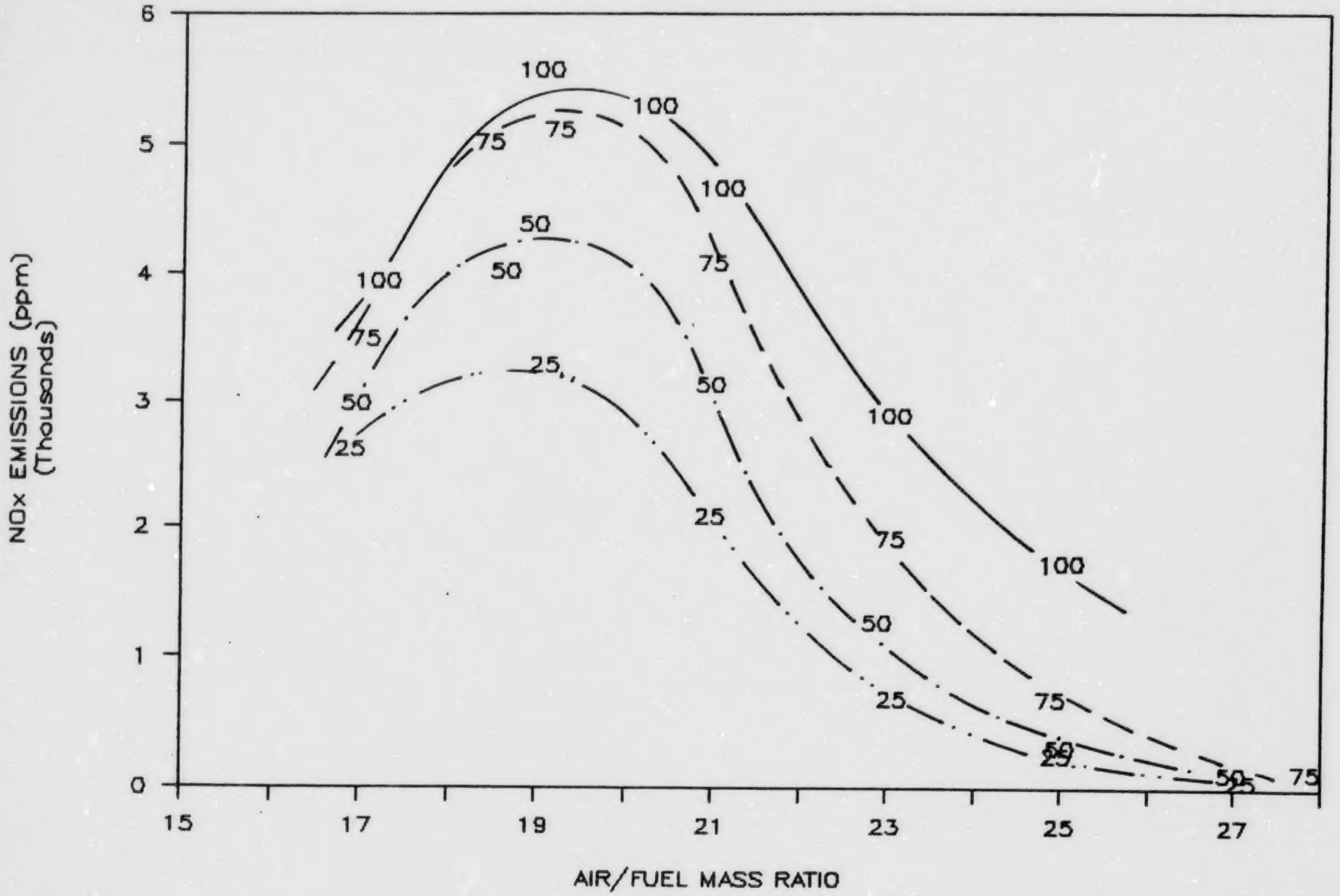
L10 NGV ENGINE THC @ 1500 RPM

BY % LOAD



L10 NGV ENGINE NOx @ 1500 RPM

BY % LOAD



Emission Characteristics of A GM 454 CID Engine Converted For Natural Gas Operation

Presented at the Fourth Windsor
Workshop on Alternative Fuels
June 20, 1988

Thomas M. Baines
US EPA MVEL Ann Arbor, MI

EMISSION CHARACTERISTICS OF A GM 454 CID ENGINE CONVERTED FOR NATURAL GAS OPERATION

T.M. Baines, US Environmental Protection Agency
Ann Arbor, Michigan

ABSTRACT

This paper presents the results of extensive emissions testing of a GM-454 CID engine that has been converted to use with natural gas. The engine was designed to be placed in a bus that is part of the Brooklyn Union Gas Company's New York City bus demonstration program.

The engine was equipped with a higher compression ratio, high energy ignition as well as a turbocharger and wastegate. It was tested with three gas mixers; a TNO closed loop, an IMPCO closed loop and an IMPCO open loop. It was tested both without a catalyst and with a catalyst which was of a "3-way" design. It was a dual bed, stainless steel supported unit with platinum and rhodium as the catalytic metals.

The engine was tested over various duty cycles as well as two intentional settings which were rich and lean of the best emissions performance settings. The emissions results from the TNO and IMPCO open loop gas mixers and with the catalyst in place were lower than the 1991 diesel bus emission standard levels. The 1991 diesel bus emission standard levels were exceeded when the engine was set up rich and lean. The energy consumption over the Heavy Duty Federal Test Procedure was higher than a diesel bus engine that it would replace.

0199B

CNG Bus Engine Testing Program Overview

- GM 454 CID Engine converted to natural gas use
- Three mixer designs
    - TNO Closed Loop
    - IMPCO Closed Loop
    - IMPCO Open Loop
- Catalyst - ECS
    - Dual Bed, Pt/Rh "3-way"
    - Engine tested with and without catalyst
- Four Test Cycles
    - Diesel Truck Cycle (HD-FTP)
    - Gasoline truck cycle
    - Bus Cycle (Central Business District)
    - Idle

CNG Engine Description

Chevrolet 454 CID Block

Compression Ratio 9.5:1 Turbo Pistons
12.78:1 at 5 psi turbo boost

High Energy Breakerless Ignition

Turbocharger Garret T04B, plus wastegate

Stainless Steel Valves

Cast Iron Exhaust Manifold

Gas Mixer Technology Overview

TNO Closed Loop

Uses Delco Microprocessor

Oxygen sensor output to determine stoichiometry

Engine set slightly rich and then leaned out with boost air bleed. This process is regulated with a value which is controlled with the microprocessor output.

IMPCO Closed Loop

Oxygen sensor output to determine stoichiometry

Engine set slightly rich and then leaned out with a dither valve in the boost sensor line that compensates the back side of the gas pressure regulator

IMPCO Open Loop

Idle gas mixture loop

Fill flow limit valve

Midrange operation A/F controlled by gas regulator pressure

Catalytic Convertor Description

"Metal Monolith" design

Stainless steel support

200 cells/in^2
0.002 inch wall thickness

2 beds, each 3.5 inches long, 7 inches diameter

1st bed 35% Rh, 65% Pt, 40g/ft^3

2nd bed 10% Rh, 90% Pt, 40g/ft^3

HD-FTP Results GM-454
CNG Engine with Various Gas Mixers

	Emissions, g/BHP-hr			
With 3-Way Cat	HC	CO	NOx	Part.
TNO Closed Loop	1.01	6.64	1.16	0.01
IMPCO Closed Loop	1.41	7.12	3.34	0.01
IMPCO Open Loop	1.03	10.77	1.33	<0.01
Without Catalyst				
TNO Closed Loop	3.57	23.29	6.87	0.01
IMPCO Closed Loop	3.73	25.25	7.12	<0.01
IMPCO Open Loop	3.55	31.90	6.62	0.01

HD-FTP Results - GM-454
CNG Engine with Various Gas Mixers

	Non-Meth. HC, g/BHP-hr	Form., mg/BHP-hr	BSEC, BTU/BHP-hr
With 3-Way Cat			
TNO Closed Loop	0.17	0.66	9,550
IMPCO Closed Loop	0.22	1.00	9,830
IMPCO Open Loop	0.15	0.80*	9,950
Without Catalyst			
TNO Closed Loop	0.83	23.24	9,810
IMPCO Closed Loop	0.85	25.38	9,540
IMPCO Open Loop	0.82	31.62	10,200

* Estimate, based on the cold start rate of 1.21mg/BHP-hr.

Table of Emissions Results and Standards

Description	Emissions, g/BHP-hr HC	CO	NOx	Part.	BSEC, BTU/BHP-hr
1991 Diesel Urban Bus Emission Standard	1.3	15.5	5.0	0.1	-
IMPCO Open Loop w/Cat.	1.03	10.77	1.33	<0.01	9,950
1988 DDEC Bus Engine Calif. Standard	0.74	1.33	5.08	0.33	8,243

Table of Emissions Results

	Emissions, q/BHP-hr				BSEC,
Description	HC	CO	NOx	Part.	BTU/BHP-hr
Rich, w/Cat.	2.50	36.60	0.25	0.01	10,750
Rich, no Cat.	5.28	56.46	5.36	0.01	10,900
Lean, w/Cat.	1.42	1.12	6.28	<0.01	9,900
Lean, no Cat.	2.94	13.04	8.09	0.01	9,810

Optimization of natural gas engines to compete in today's low emissions environment is in its early stages.

- Catalyst failures - twice at EPA
- Critical components have unproven durability - e.g., values that control A/F, catalysts under the high CNG exhaust temperatures (1250°F or more)
- Results of component failure can be higher HC and NOx and very high CO
- In-use emissions are a question

  + translating laboratory settings to in-use engines
  + durability of settings in-use

Conclusions

- The CNG engine that was tested had emissions results below the 1991 diesel bus engine emissions standard levels

- This was achieved after considerable optimization by the gas mixer manufacturers

- Compared to a state-of-the-art diesel bus engine that would be replaced by this engine, the particulate and NOx levels are much lower, but the CO and energy consumption levels are much higher

- There are significant durability questions that have yet to be answered. These include the catalyst and A/F control components.

- In-use engine settings and the durability of these settings are other questions that have not been answered.

- The consequences of component failure or improper engine settings is high emissions of CO, HC and NOx

EXHAUST EMISSION CHARACTERISTICS OF NATURAL GAS DUAL FUELLED HEAVY DUTY DIESEL ENGINE

C. Perry, L. Gettel
B.C. RESEARCH

NO PAPER AVAILABLE

SLIDE I

GAS SOLUBILITIES

VERY SOLUBLE - GASES IN H_2O

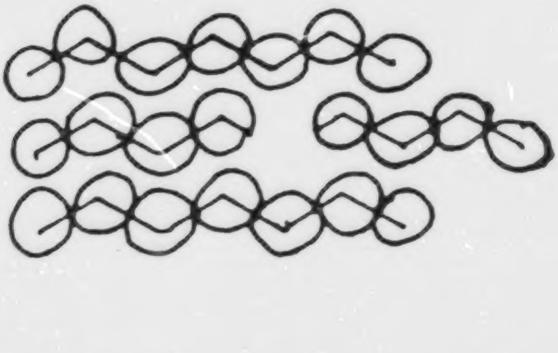
$NH_3 + H_2O$ == NH_4OH solution

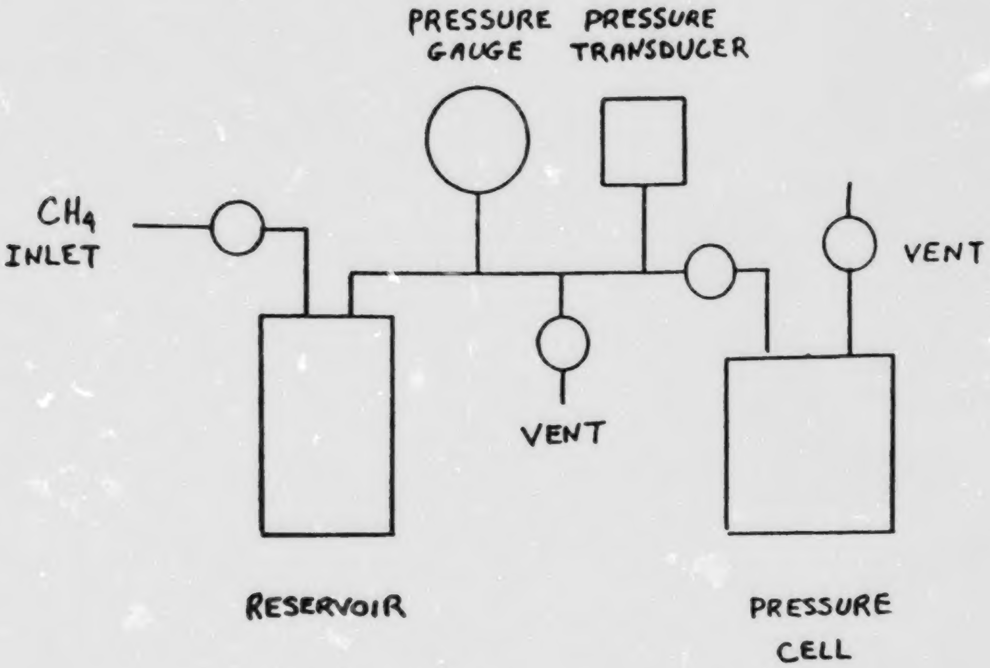
∿ 50 moles in one litre of ∿ 1120 L/L

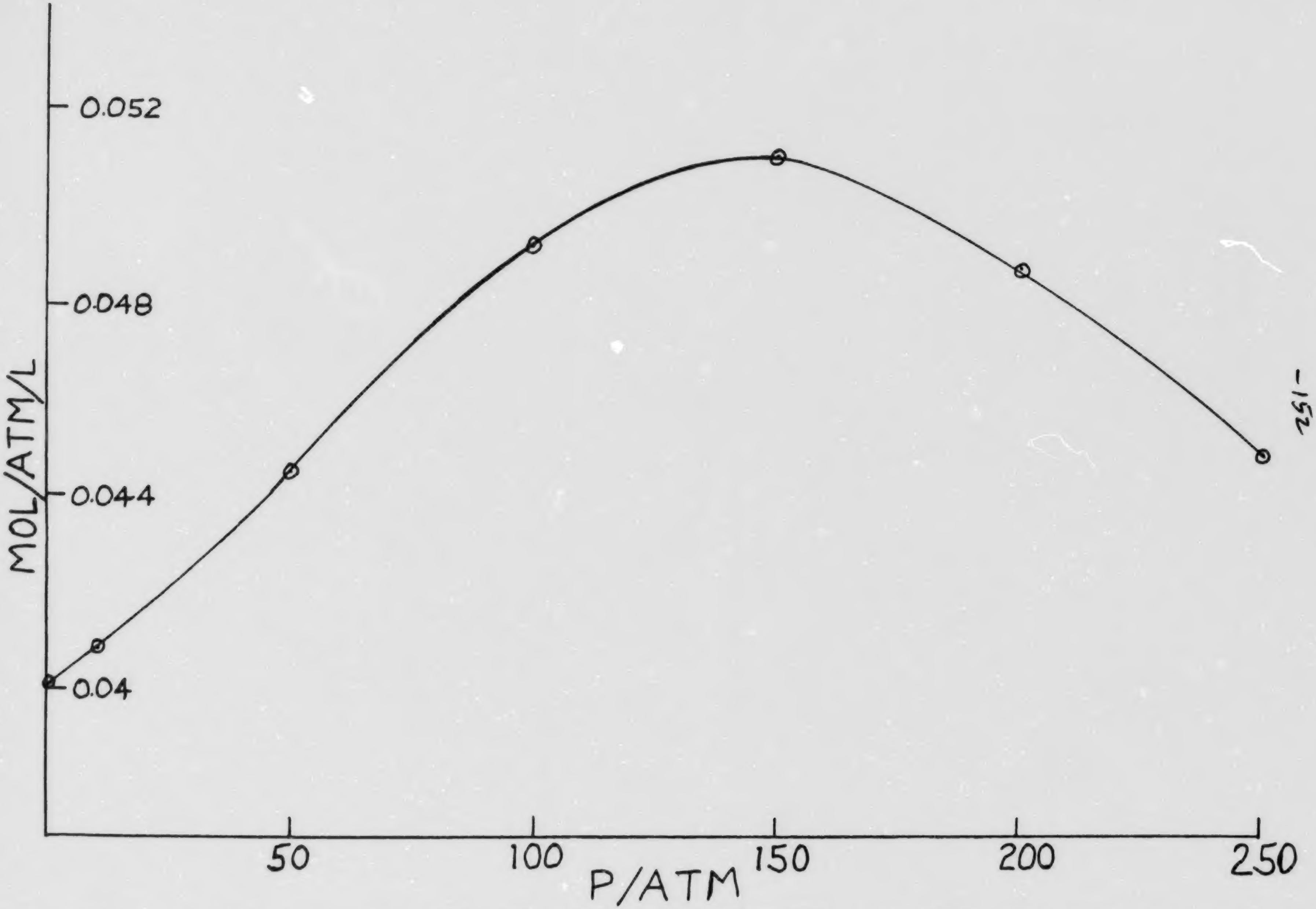
$HCl + H_2O$ == HCl solution

∿ 23 mole in one litre or ∿ 510 L/L

Hydrocarbon Gases in Hydrocarbons




PRESSURE GAUGE
PRESSURE TRANSDUCER
CH$_4$ INLET
VENT
VENT
RESERVOIR
PRESSURE CELL



-152

[illegible] ?

-153-

Typical Spread Sheet

EXPERIMENT #66: APR1801
49.3 mL Petrocan Regular
Corrected for Volume and Density Changes

V1/mL= 131.4 V2/mL= 18.2 T/K= 296.6 Vol/mL= 49.3 d/(g/mL)= 0.724

Pi/atm	Pf/atm	N1i/mol	N1f/mol	N2i/mol	N2f/mol	N1iq/mol	Ntot/mol	mol/atm/kg	mol/atm/L	xy	x2
6.220	4.621	0.033976	0.025161	0.000743	0.003374	0.006183	0.006183	0.0478	0.0344	0.028576	21.353
9.465	7.975	0.052055	0.043726	0.003374	0.005724	0.005978	0.012162	0.0488	0.0350	0.096997	63.600
12.814	11.335	0.070974	0.062584	0.005724	0.007993	0.006121	0.018283	0.0495	0.0354	0.207246	128.482
16.032	14.607	0.089407	0.081214	0.007993	0.010120	0.006066	0.024350	0.0501	0.0356	0.355680	213.364
19.583	18.086	0.110048	0.101309	0.010120	0.012289	0.006570	0.030920	0.0507	0.0358	0.559221	327.103
22.897	21.441	0.129597	0.120972	0.012289	0.014288	0.006625	0.037545	0.0514	0.0362	0.805023	459.716
26.204	24.762	0.149390	0.140721	0.014288	0.016176	0.006780	0.044326	0.0522	0.0366	1.097623	613.156
29.620	28.157	0.170138	0.161214	0.016176	0.018011	0.007088	0.051415	0.0530	0.0369	1.447714	792.816
33.158	31.682	0.191962	0.182814	0.018011	0.019811	0.007347	0.058763	0.0536	0.0371	1.861745	1.003e03
36.527	35.118	0.213057	0.204198	0.019811	0.021461	0.007208	0.065972	0.0541	0.0373	2.316821	1.233e03
40.017	38.602	0.235254	0.226213	0.021461	0.023026	0.007476	0.073449	0.0547	0.0374	2.835290	1.490e03
43.386	42.018	0.256997	0.248129	0.023026	0.024450	0.007443	0.080892	0.0552	0.0376	3.398951	1.765e03
46.890	45.502	0.279964	0.270825	0.024450	0.025789	0.007800	0.088692	0.0558	0.0377	4.035700	2.070e03
50.061	48.775	0.301052	0.292464	0.025789	0.026939	0.007437	0.096130	0.0563	0.0379	4.688777	2.379e03
	372.681						689.0908	0.0571	0.0414	23735.36	1.256e04

N= 14 5391.720 2640.8816 slope= 2.0416 intercept -5.127

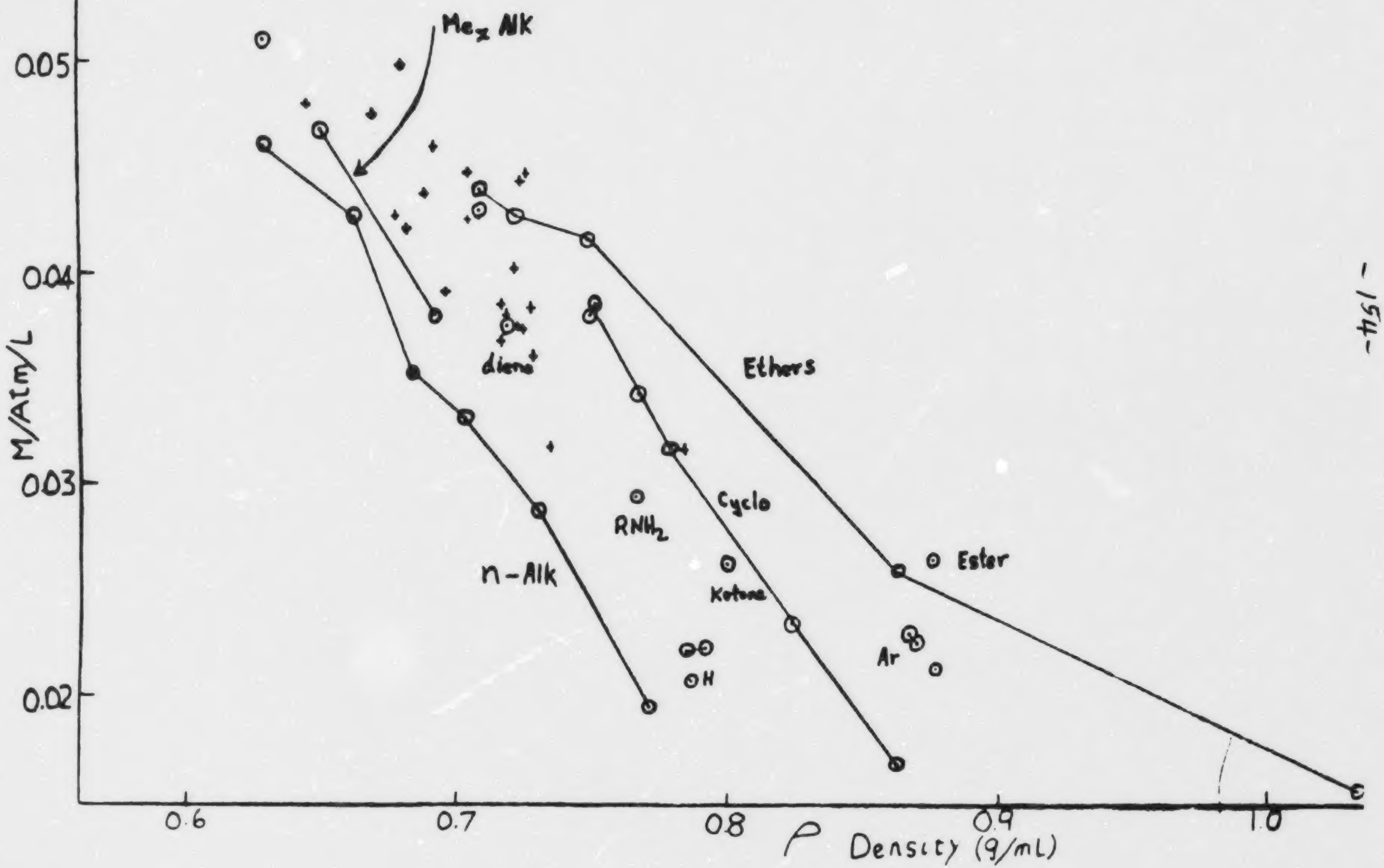
P1i/atm	P2i/atm	Pf/atm		C1i	C2i	Cf	V2/mL	xy	x2
6.220	1.000	5.575	86.84	1.01289	1.00204	1.01153	18.72	104.403	31.080
9.465	4.621	8.880	79.85	1.01978	1.00953	1.01852	18.23	161.928	78.854
12.814	7.975	12.237	79.87	1.02700	1.01660	1.02575	17.97	219.907	149.744
16.032	11.335	15.496	75.25	1.03406	1.02379	1.03287	17.10	264.983	240.126
19.583	14.607	19.023	79.79	1.04197	1.03092	1.04072	16.83	320.317	361.874
22.897	18.086	22.360	77.66	1.04948	1.03862	1.04825	16.68	373.117	499.969
26.204	21.441	25.694	74.82	1.05709	1.04617	1.05591	15.92	409.080	660.181
29.620	24.762	29.117	74.90	1.06506	1.05376	1.06388	15.33	446.604	847.799
33.158	28.157	32.648	77.12	1.07345	1.06163	1.07224	15.08	492.365	1.065e03
36.527	31.682	36.037	75.22	1.08155	1.06994	1.08037	14.93	538.354	1.298e03
40.017	35.118	39.541	74.25*	1.09005	1.07815	1.08888	14.29	565.426	1.563e03
43.386	38.602	42.930	72.18	1.09835	1.08659	1.09722	13.99	600.672	1.842e03
46.890	42.018	46.434	73.35	1.10709	1.09497	1.10594	13.72	637.261	2.156e03
50.061	45.502	49.653	66.50	1.11507	1.10362	1.11404	13.04	647.628	2.465e03
					1.11182				

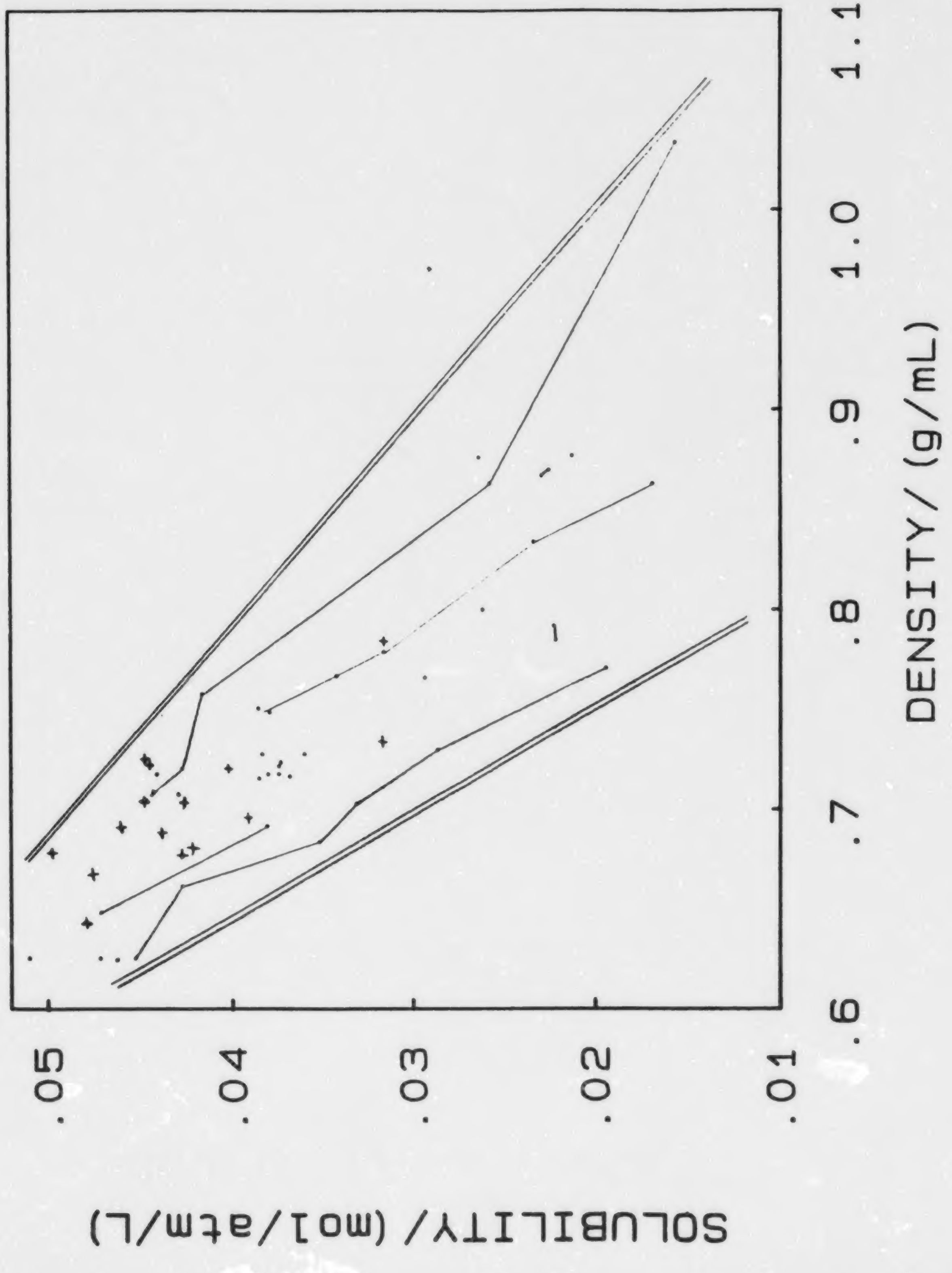
Avg. V2= 15.84 mL

		385.62					221.89	5782.05	1.326e04

-330.011 2640.2973 slope= -0.124 intercept= 19.29

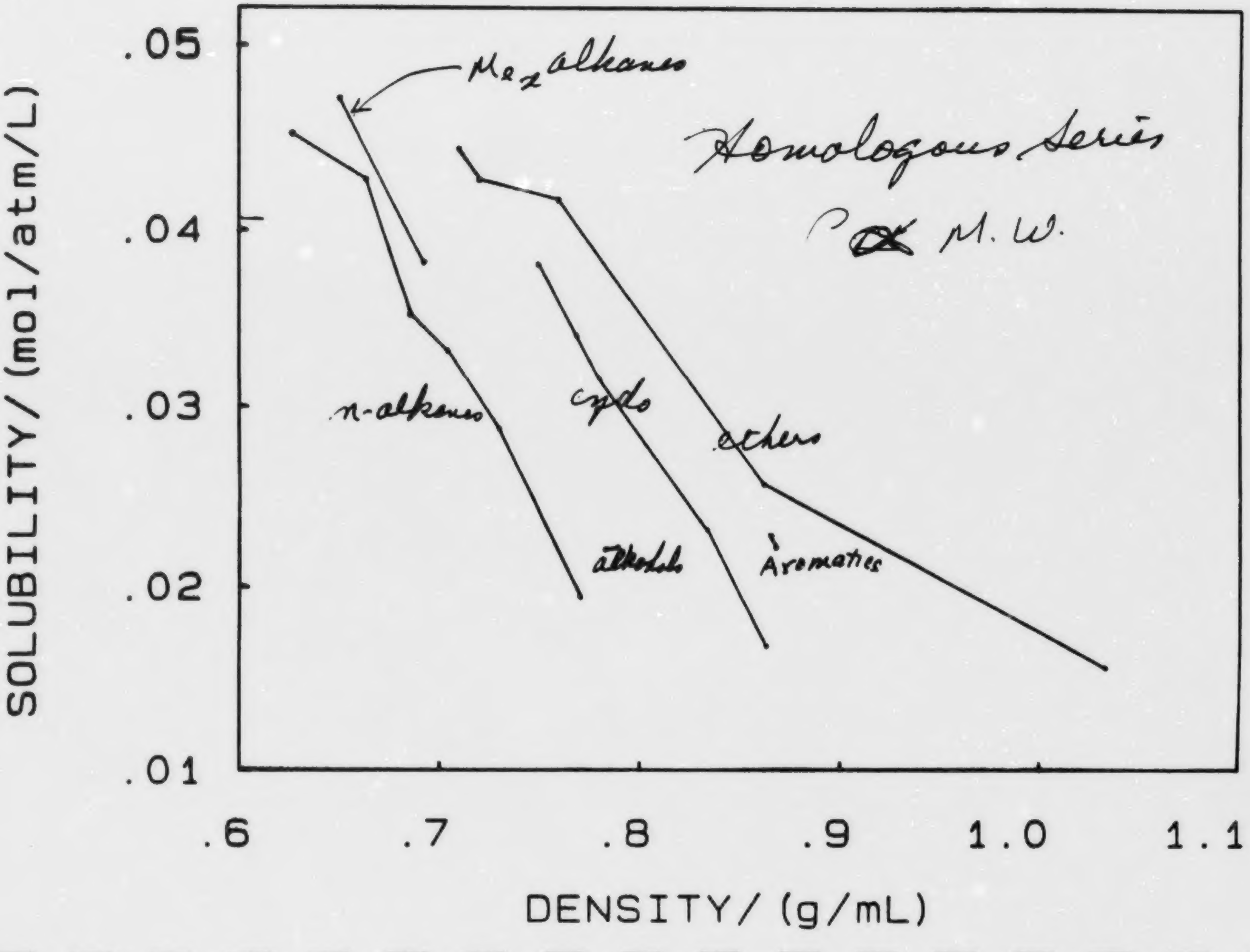
⑤


M/Atm/L
0.05
0.04
0.03
0.02
0.6
0.7
0.8
0.9
1.0
ρ Density (g/mL)
Me$_x$ Alk
diene
n-Alk
RNH$_2$
Cyclo
Ketone
OH
Ethers
Ester
Ar


SOLUBILITY/ (mol/atm/L)
.05
.04
.03
.02
.01
DENSITY/ (g/mL)
.6
.7
.8
.9
1.0
1.1

(7) ?

F 10


SOLUBILITY/ (mol/atm/L)
.05
.04
.03
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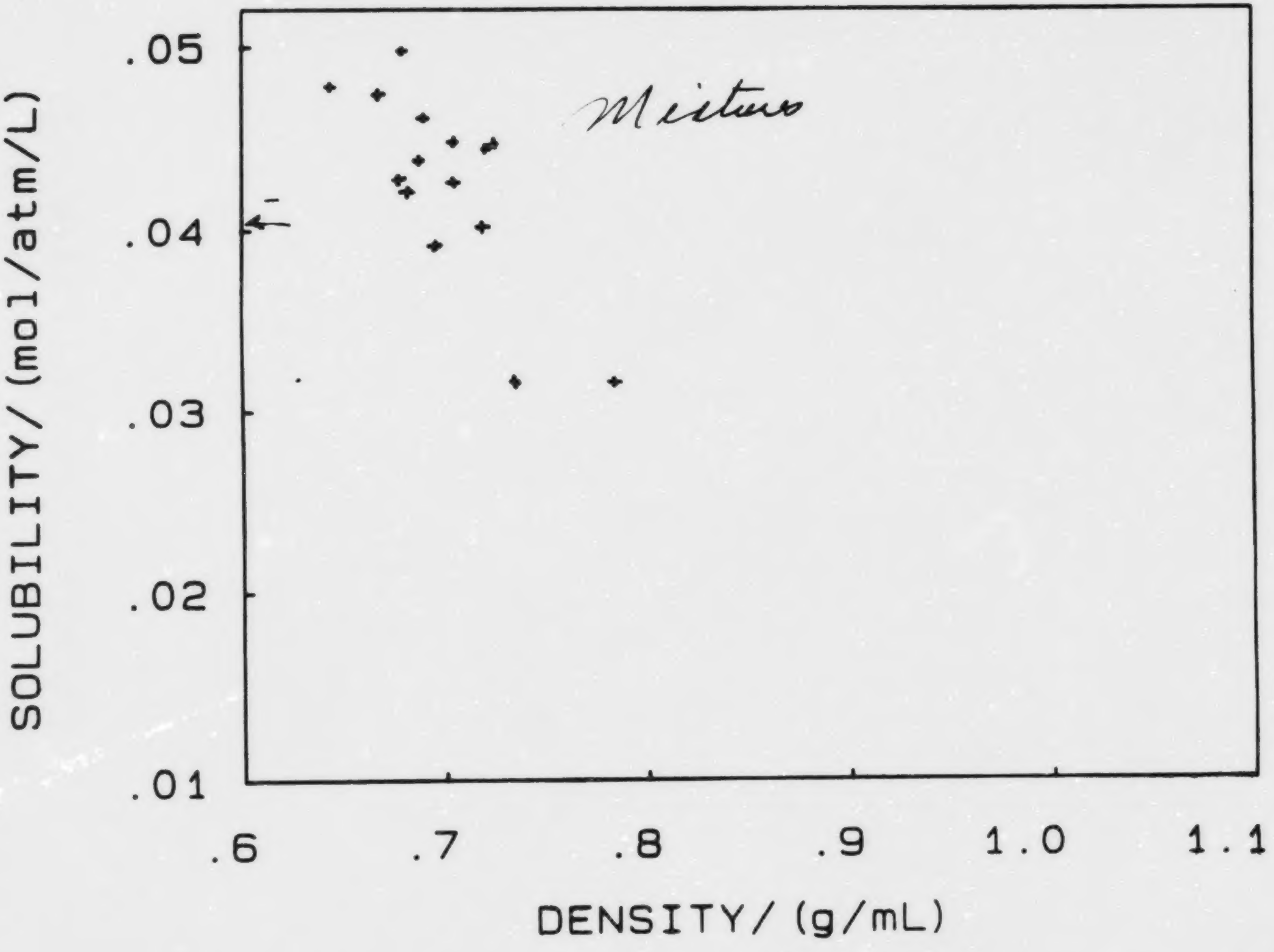
.01
DENSITY/ (g/mL)
.6
.7
.8
.9
1.0
1.1
Me_x alkanes
n-alkanes
cyclo
ethers
alkohols
Aromatics
Homologous Series
C ~~α~~ M.W.

(11)


SOLUBILITY/ (mol/atm/L)
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.04
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DENSITY/ (g/mL)
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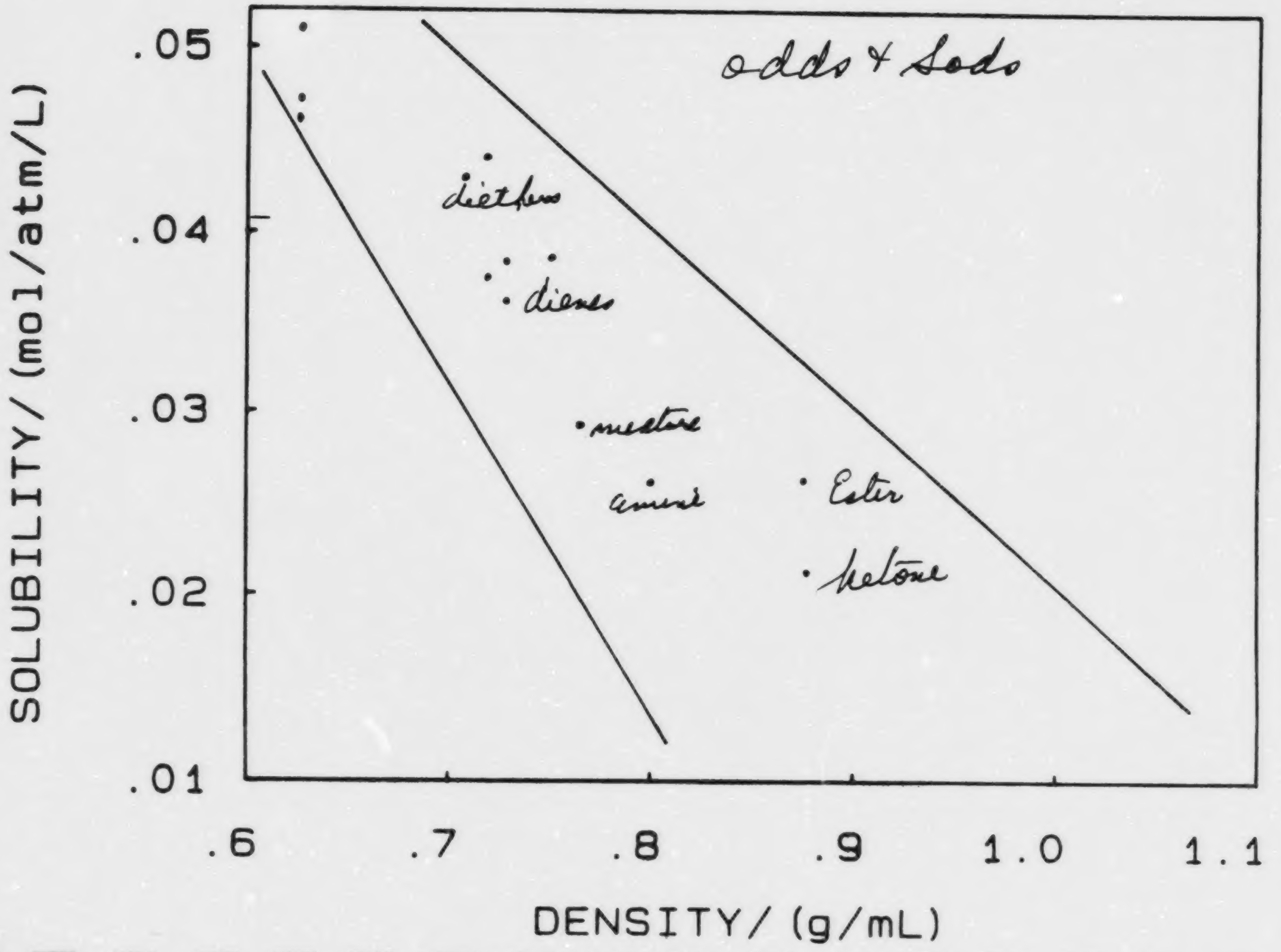
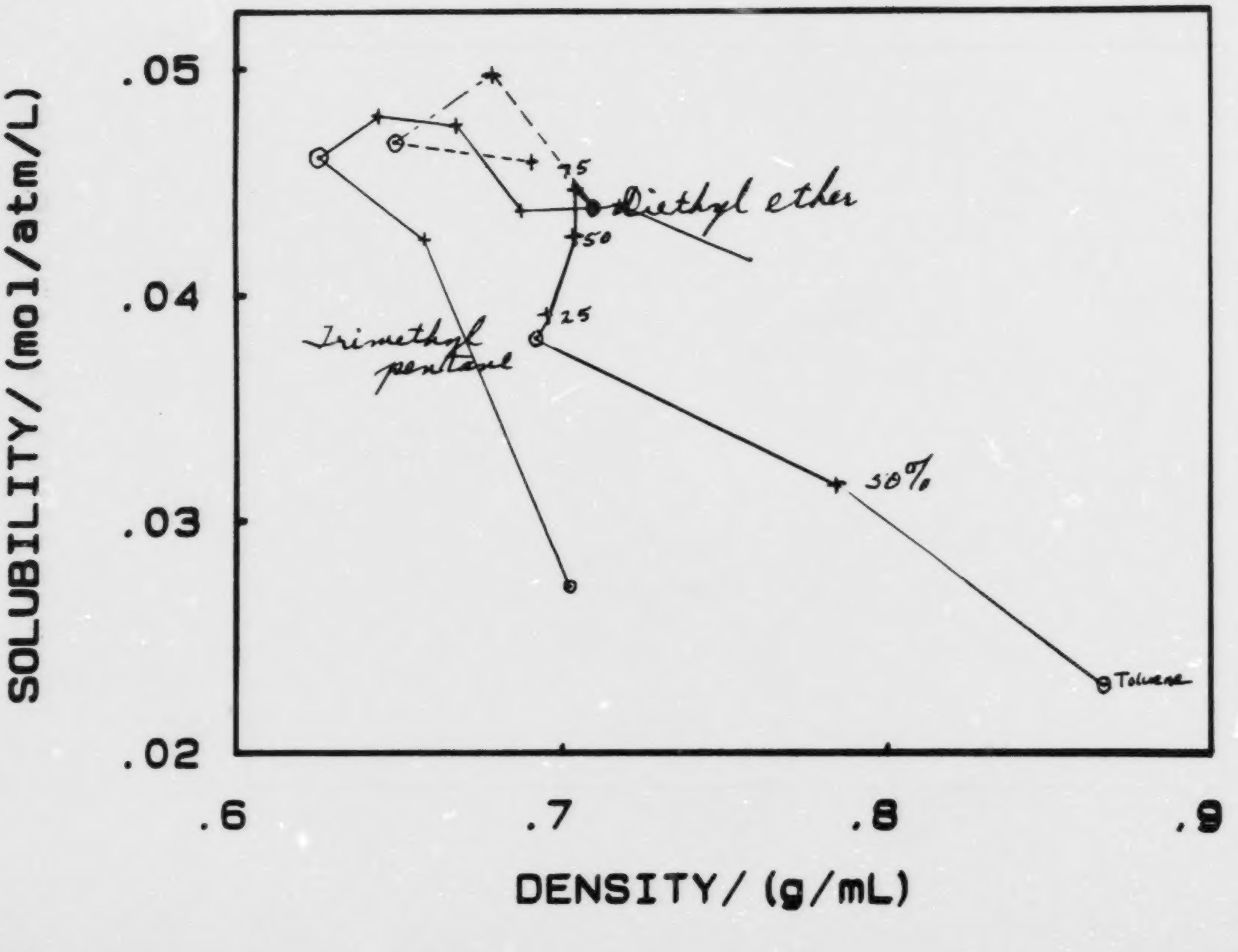
1.0
1.1
Mixtures

(4)

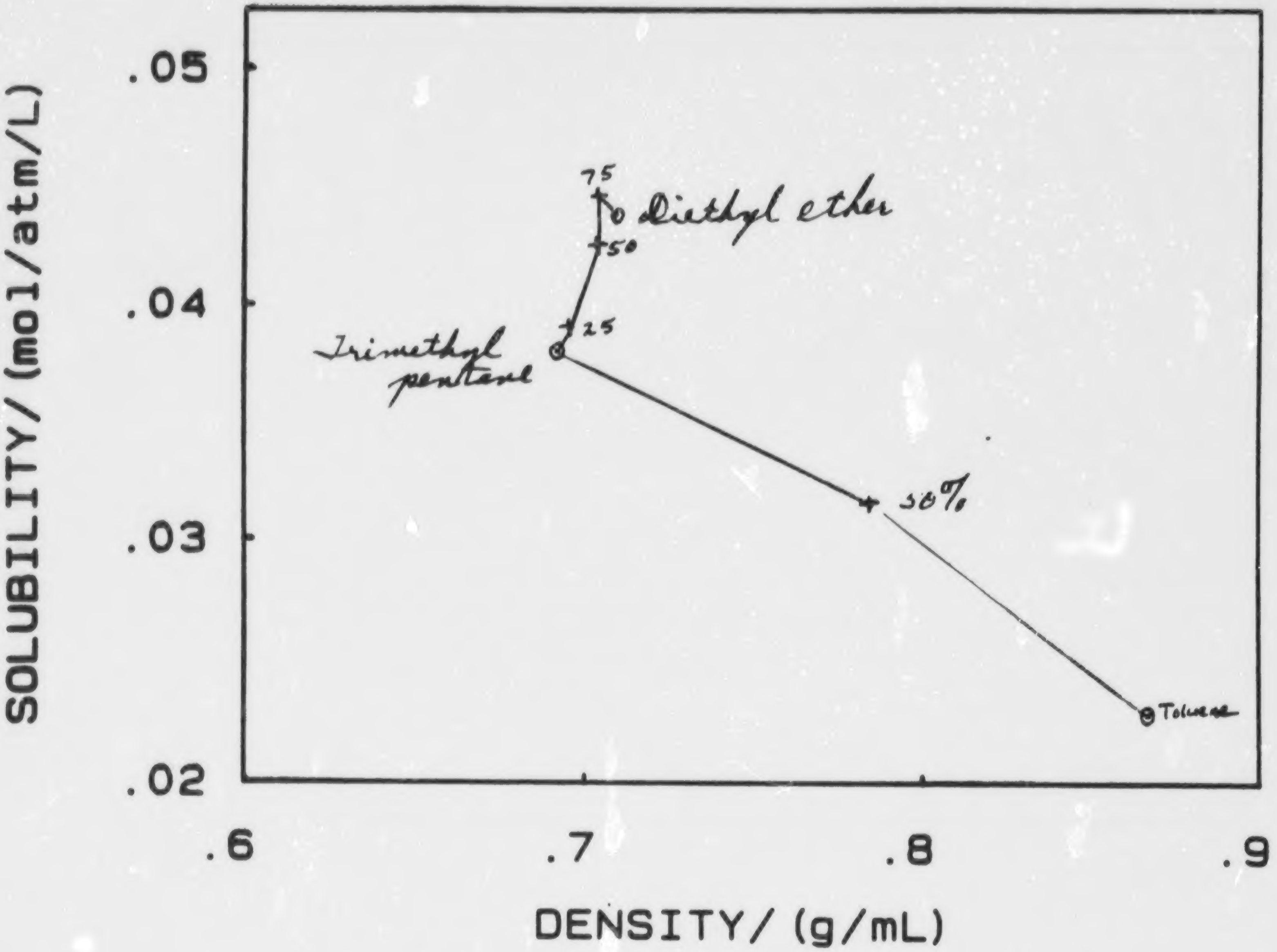
2
13


odds + Sods
diethers
dienes
mixture
amine
Ester
ketone
.05
.04
.03
.02
.01
SOLUBILITY/ (mol/atm/L)
.6
.7
.8
.9
1.0
1.1
DENSITY/ (g/mL)


SOLUBILITY/ (mol/atm/L)
.05
.04
.03
.02
.6
.7
.8
.9
DENSITY/ (g/mL)
Diethyl ether
75
50
25
Trimethyl pentane
50%
Toluene

?(11)?

Fi. 16 TB


SOLUBILITY/ (mol/atm/L)
.05
.04
.03
.02
.6
.7
.8
.9
DENSITY/ (g/mL)
75
50
25
Diethyl ether
Trimethyl pentane
50%
Toluene

L10 Methanol Engine With 'AVOCET' - An Update

V K Duggal
Cummins Engine Company

A Welch
Ontario Research Foundation

Abstract

The presentation reviews the development of a Cummins methanol L10 engine operating with ignition and lubricating additives (Avocet) mixed with the fuel. An additive concentration of 5 % on volume basis has been used for most of the tests reported here.

The discussion includes performance, emissions and cold start characteristics of the engine configured for a transit bus application. The changes made to the base diesel engine include: fuel pump, cam and injectors. These are designed essentially to deliver larger fuel volume and material compatibility with methanol.

The results indicate that the engine performance and efficiency is similar to base diesel engine. The cylinder pressure development is smooth. Test bed experiments carried out to evaluate the impact of low or no additive concentration in the fuel show an expected increase in ignition delay. The cold start tests show good cold start capability down to 1 % additive. The injection equipment optimization has resulted in significant improvements in emissions of unburnt hydrocarbons and NOx measured on steady state cycle.

A configuration of L10 methanol engine is ongoing field trials in Vancouver.

V. K. Duggal

L10 METHANOL ENGINE WITH 'AVOCET'

- AN UPDATE

V. K. DUGGAL

CUMMINS ENGINE COMPANY, INC.

A. WELCH

ONTARIO RESEARCH FOUNDATION

FOURTH WINDSOR WORKSHOP-ALTERNATE FUELS
WINSOR, ONTARIO, JUNE 20-22, 1988

ACKNOWLEDGEMENTS

THE WORK HAS BEEN SUPPORTED BY MTO AND CUMMINS ENGINE COMPANY. THE DESIGN AND DEVELOPMENT EFFORTS OF J. R. MCDONALD AND P. GUZMAN (CUMMINS) HAVE SIGNIFICANTLY CONTRIBUTED TO THE PROGRESS OF THIS WORK.

OUTLINE

- BACKGROUND RECAP
- PERFORMANCE/EMISSIONS OPTIMIZATION
    - ENGINE EFFICIENCY
    - CYLINDE PRESSURE
    - COLD START
    - EMISSIONS
- ENGINE STATUS/ISSUES

Objectives

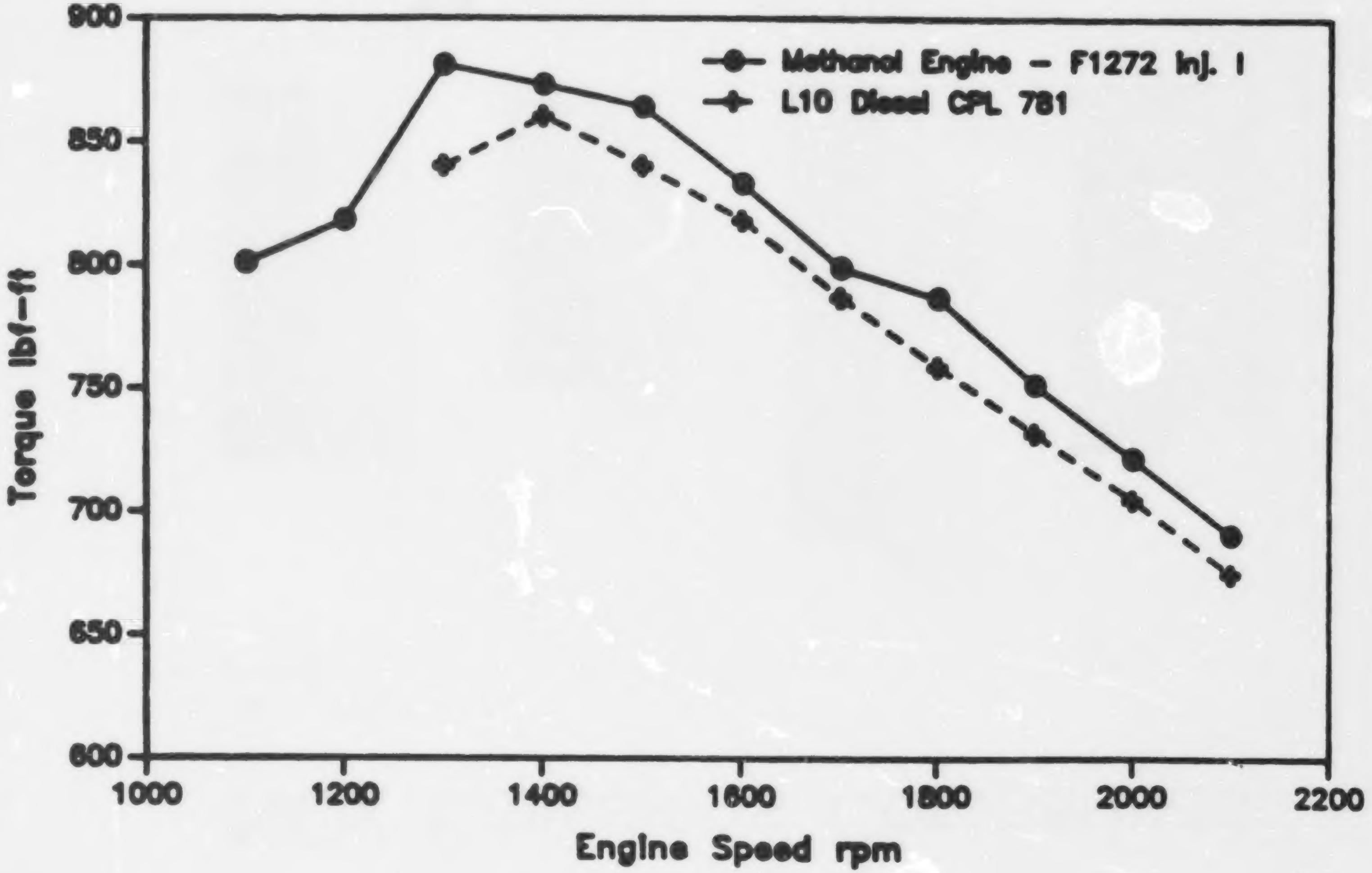
- Demonstrate a methanol engine with minimum engine change
- Develop performance and emissions data base
- Optimize engine combustion/performance
- Field test

METHANOL ENGINE TECHNOLOGY

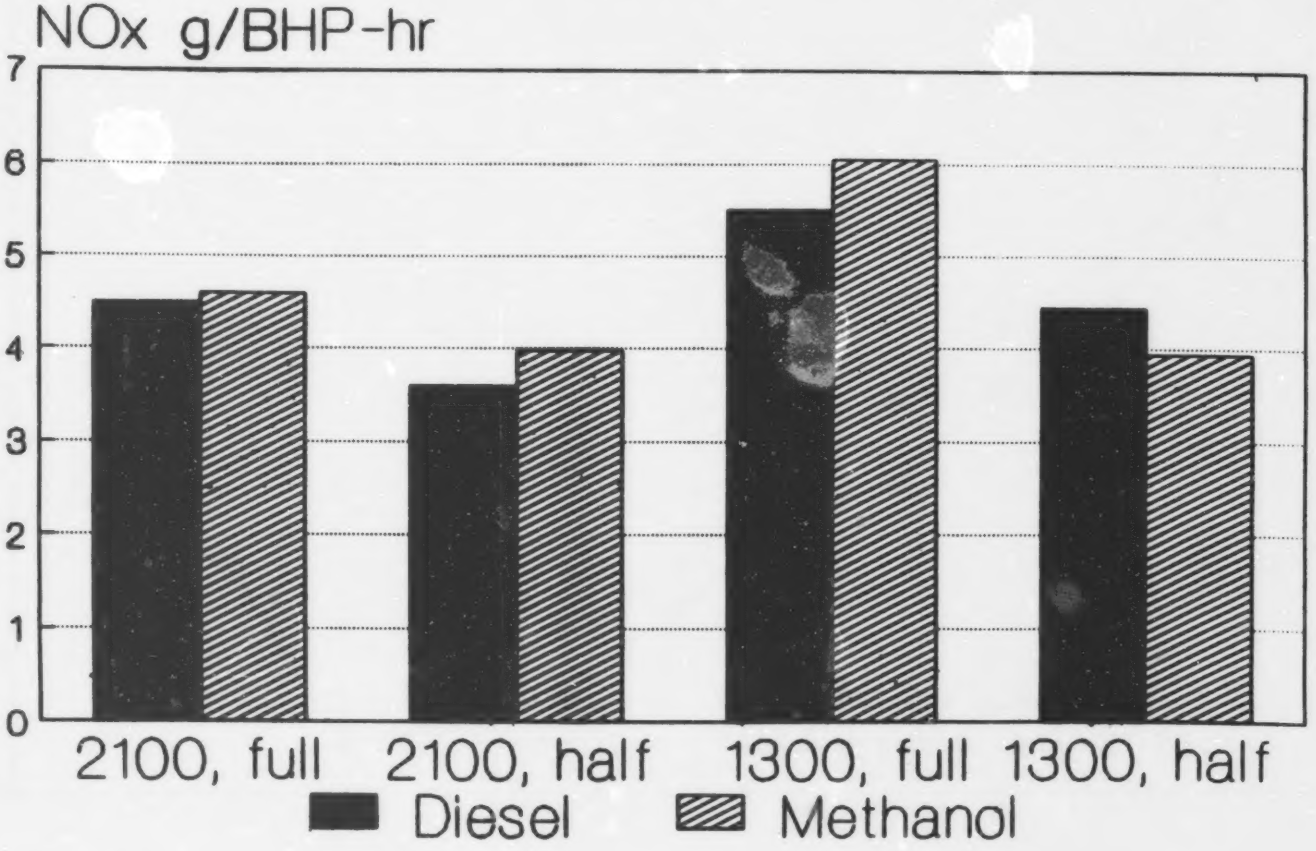
STRATEGY:

FUEL MODIFICATION TO COMPRESSION IGNITE METHANOL

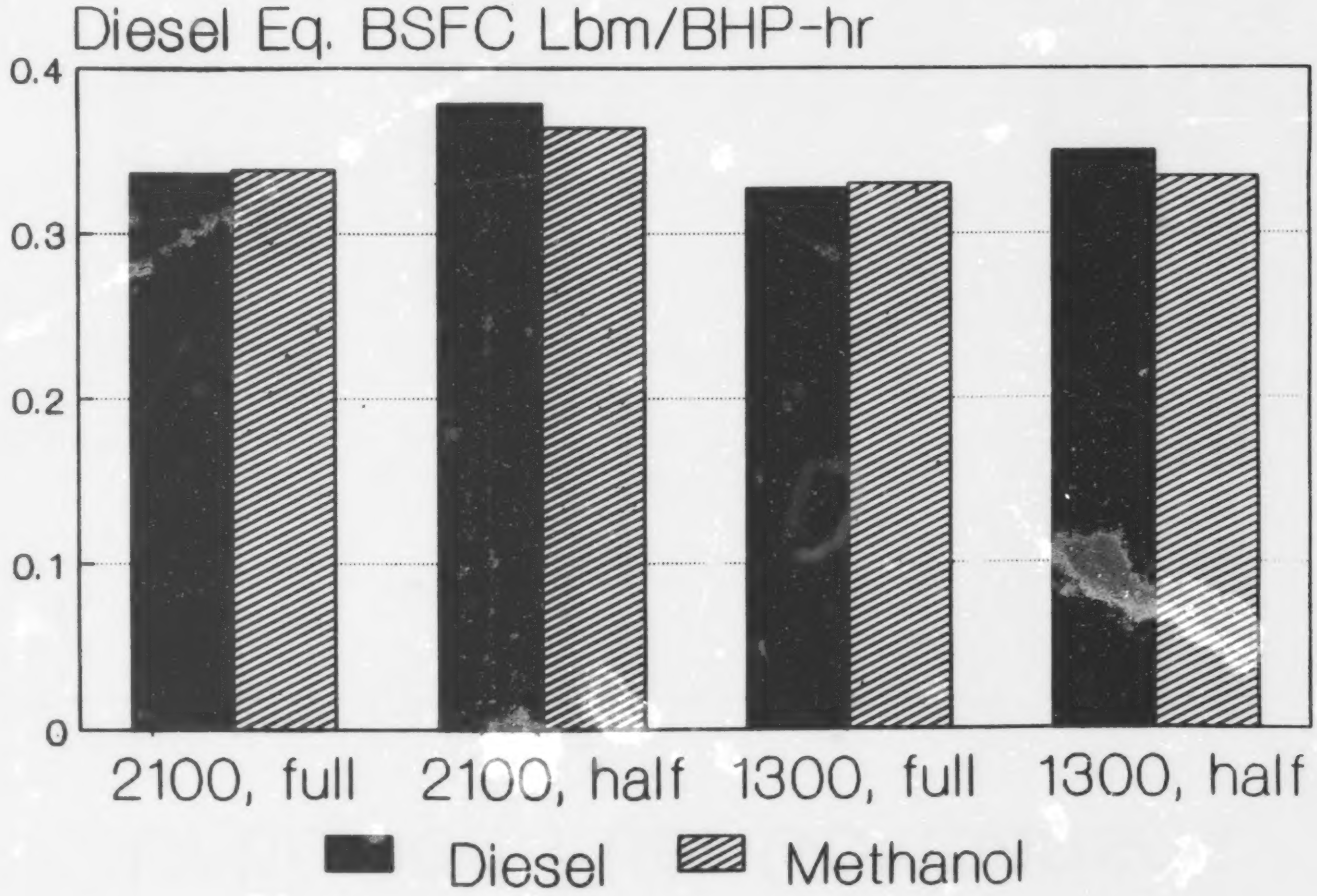
- ADDITIVE PACKAGE: TEGDN (BRAZIL) AVOCET (ICI, UK)
- ENGINE MODIFICATIONS: CAM, INJECTORS AND FUEL PUMP


L10 Methanol Torque Curve

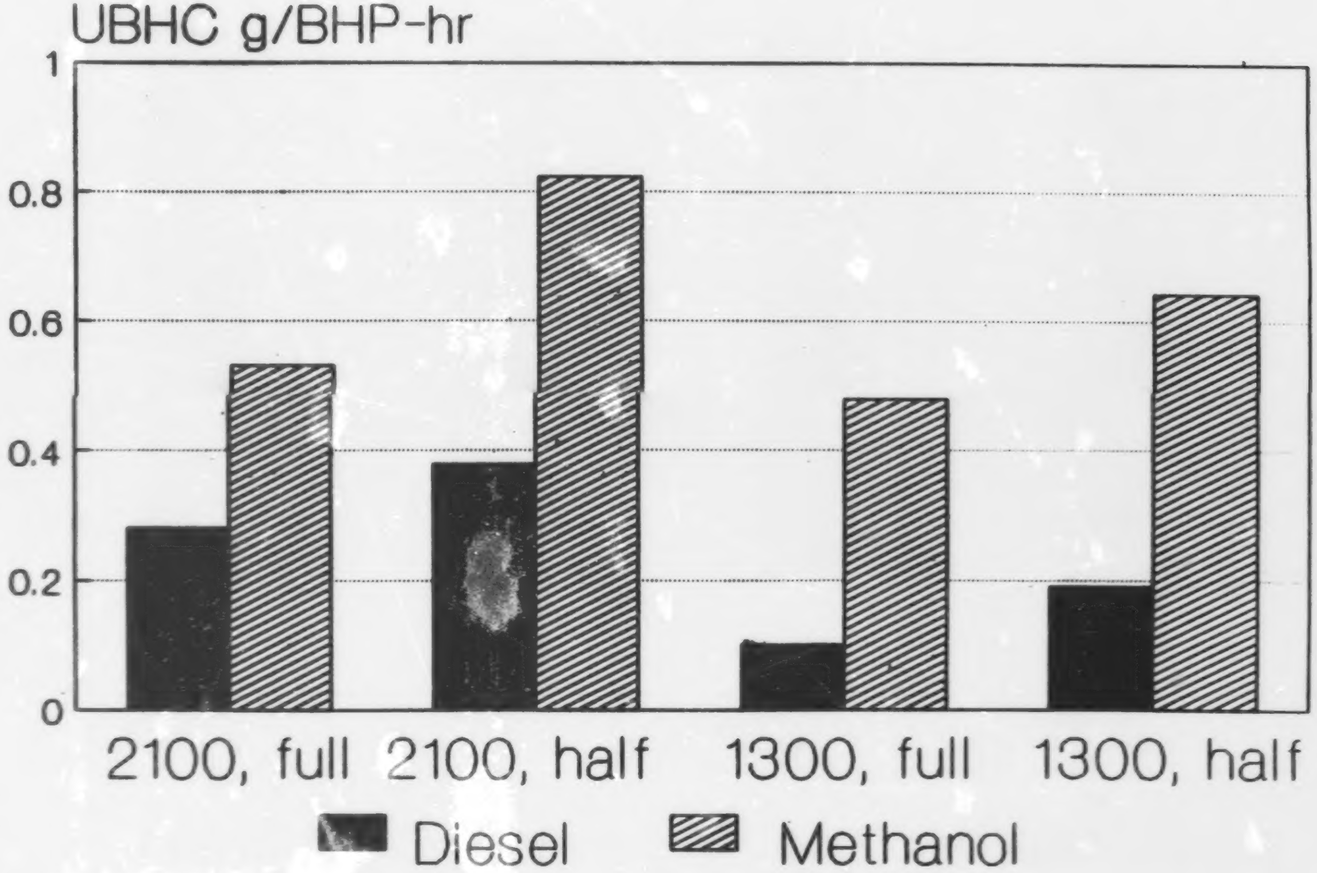
NOx Emissions Comparison



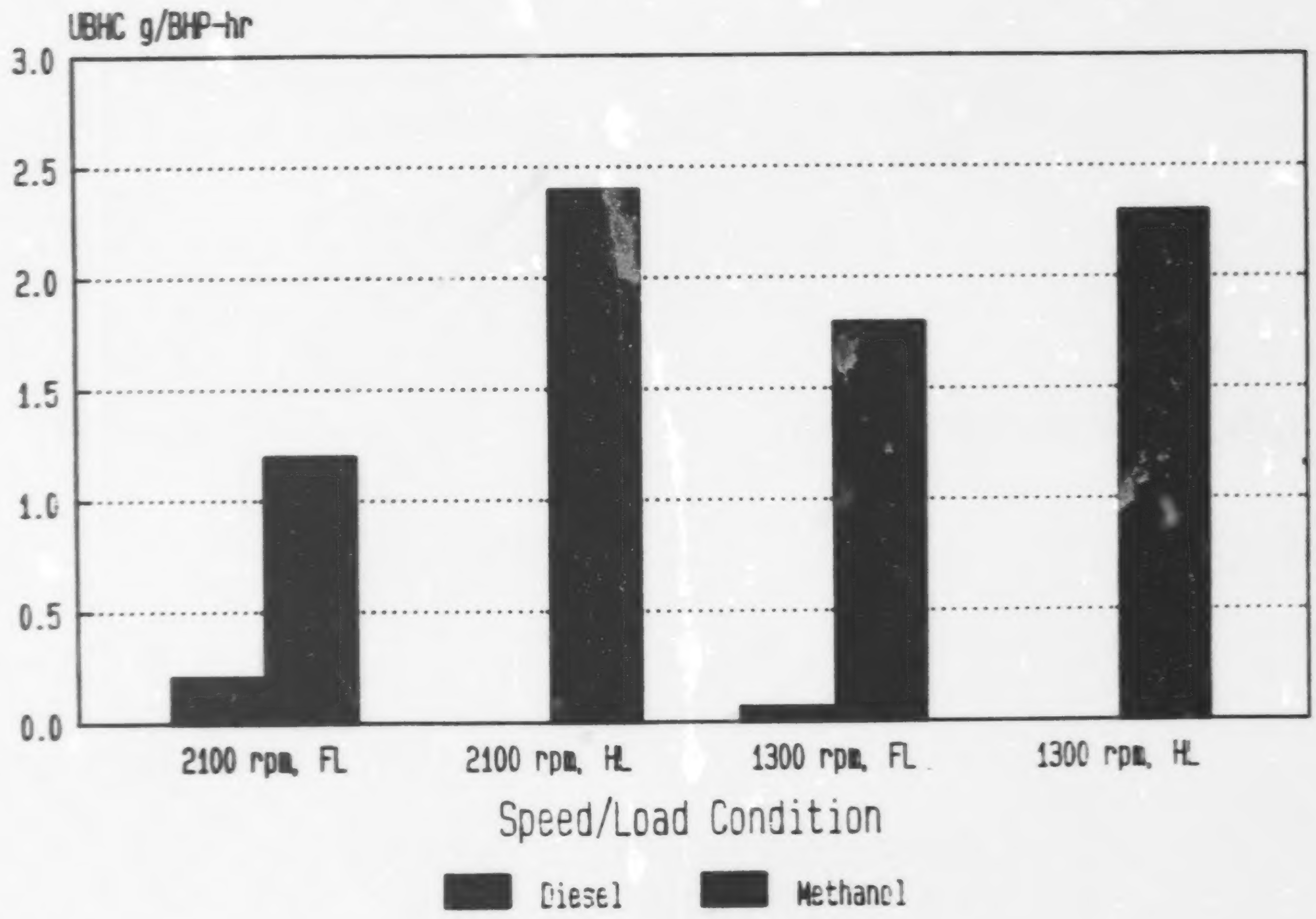
Diesel Equivalent BSFC Comparison



Unburned Fuel Comparison

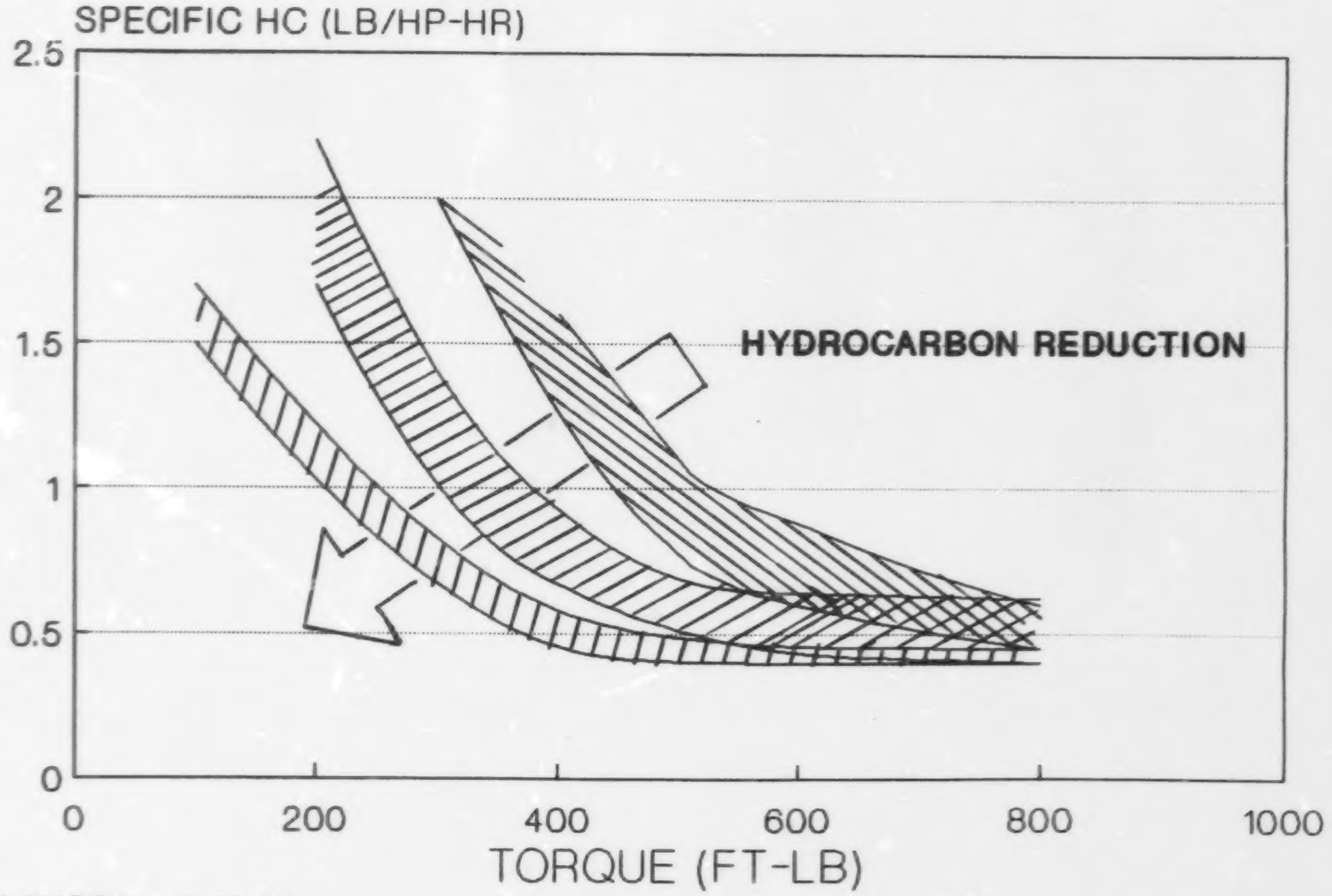


Unburned Fuel Comparison



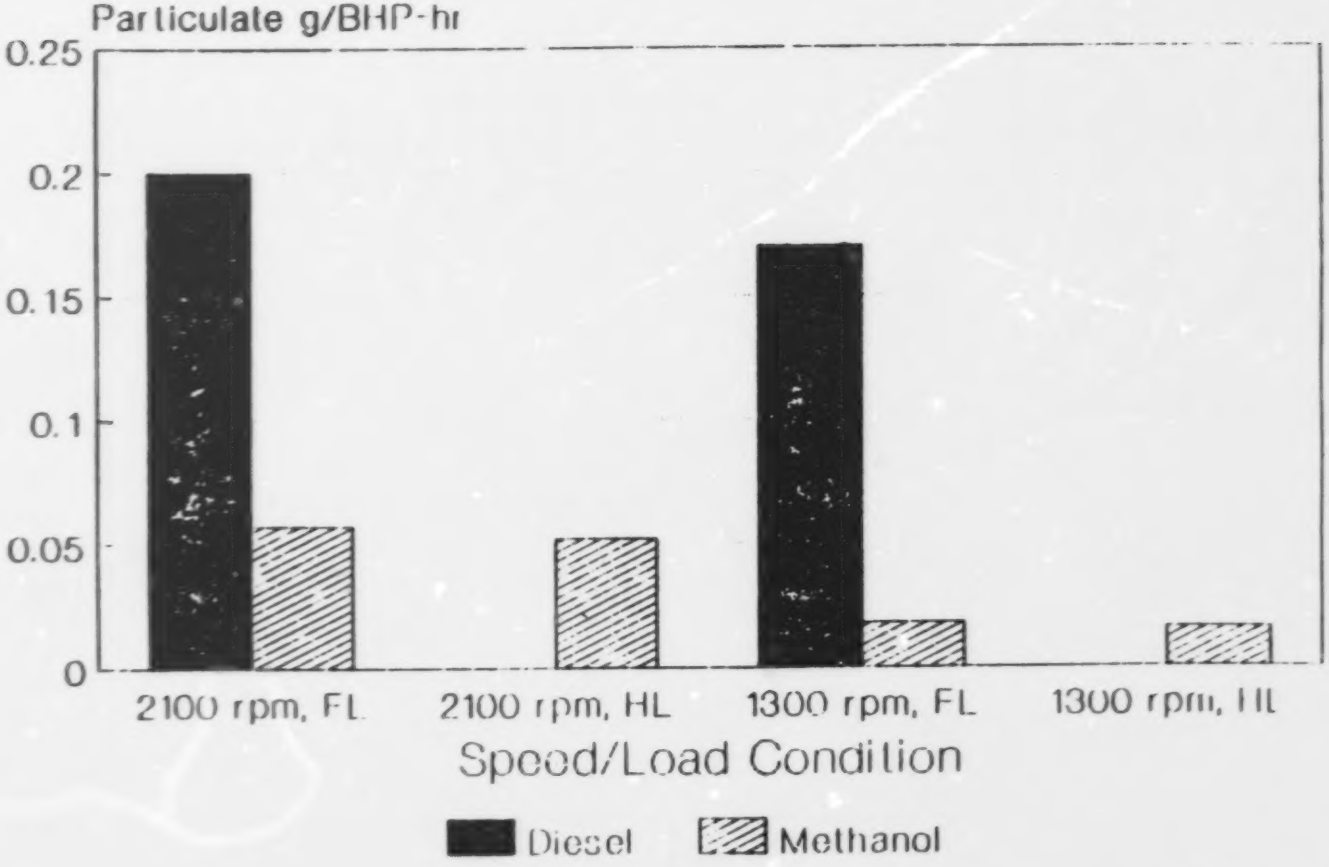
Data from ORF

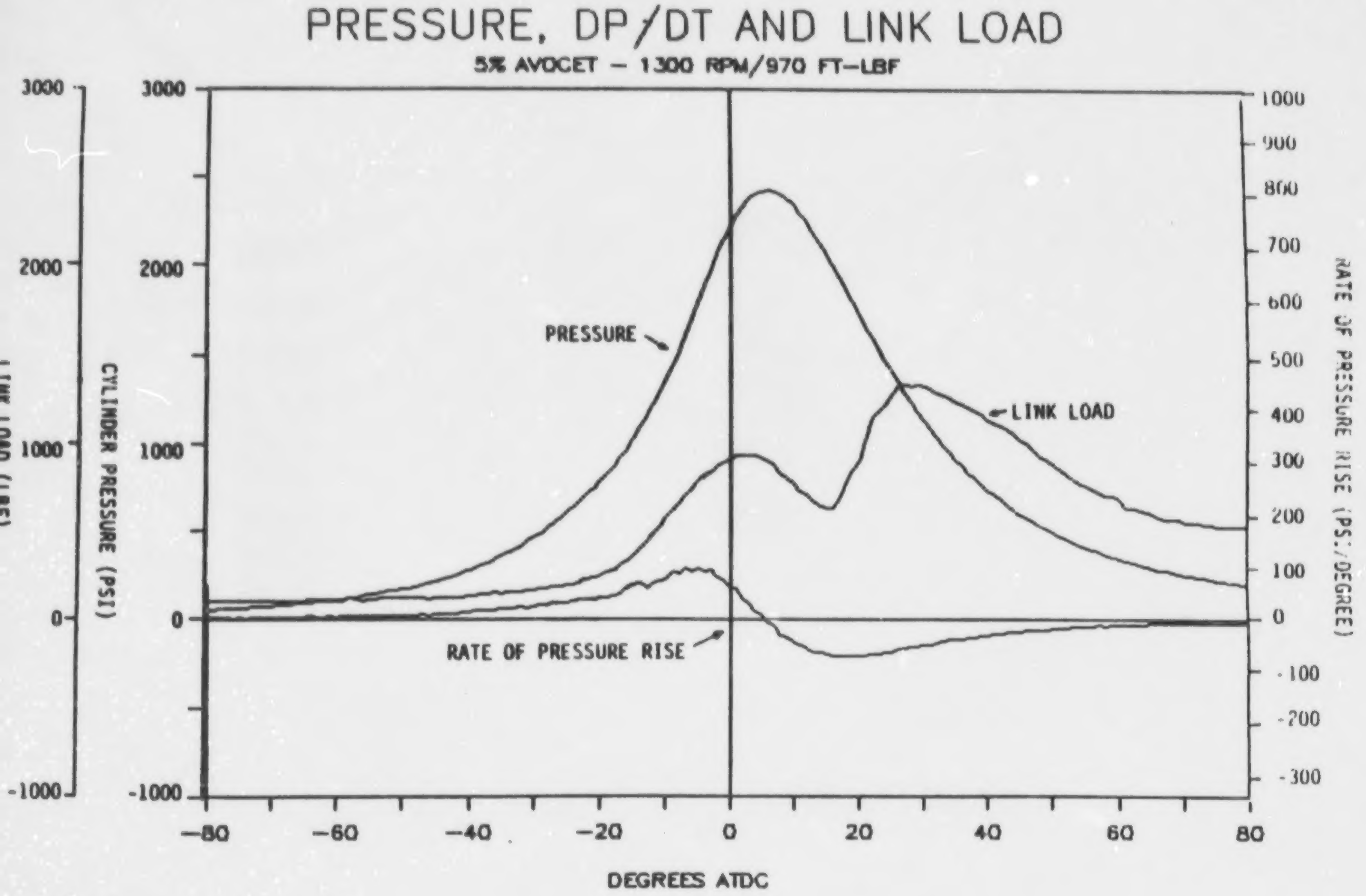
ADDITIVE METHANOL L10
HYDROCARBON EMISSIONS



.. V K DUGGAL 6-17-88

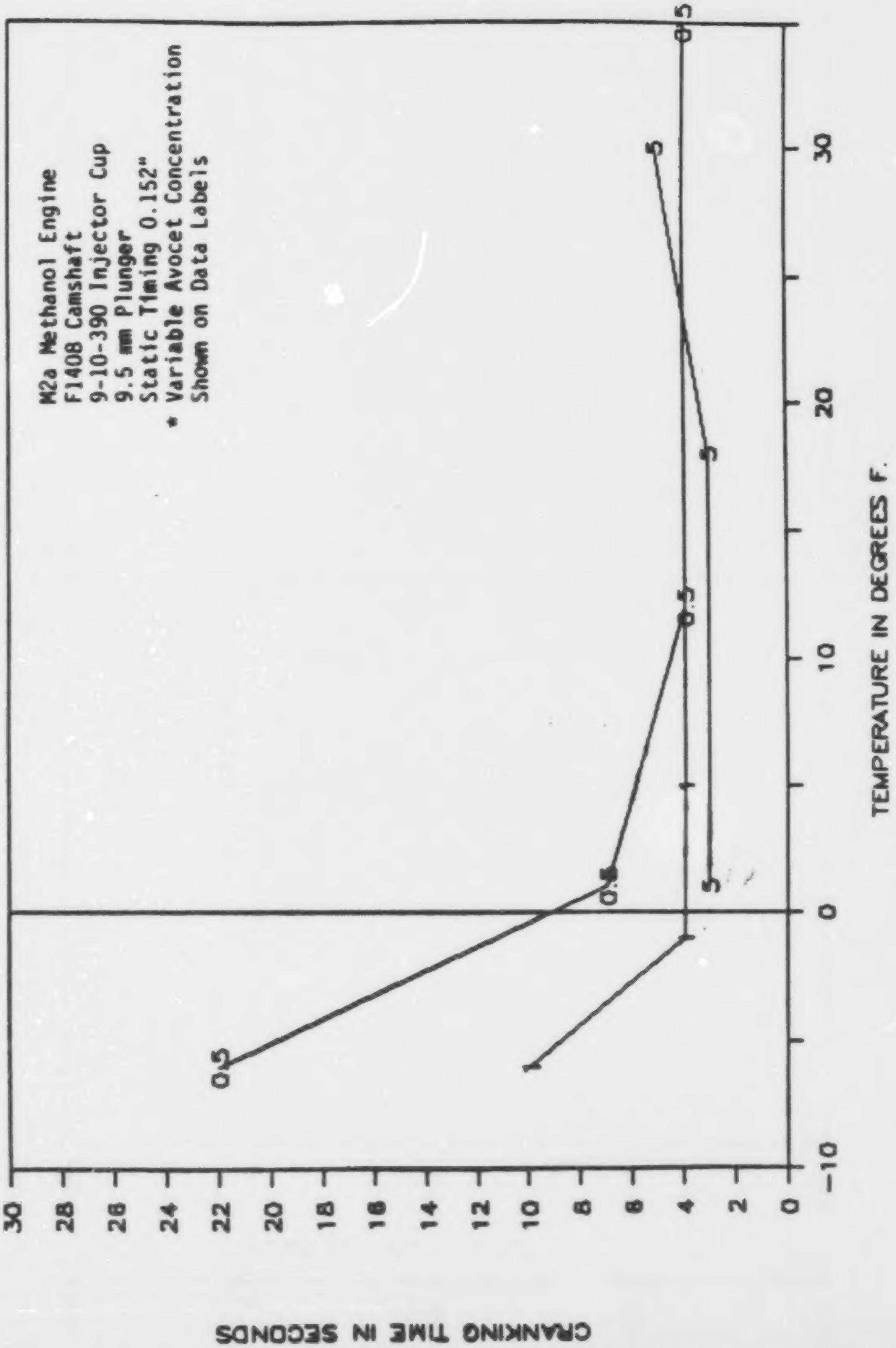
Particulate Comparison




PRESSURE, DP/DT AND LINK LOAD
5% AVOCET – 1300 RPM/970 FT–LBF
LINK LOAD (LBF)
3000
2000
1000
0
-1000
CYLINDER PRESSURE (PSI)
3000
2000
1000
0
-1000
RATE OF PRESSURE RISE (PSI/DEGREE)
1000
900
800
700
600
500
400
300
200
100
0
-100
-200
-300
PRESSURE
LINK LOAD
RATE OF PRESSURE RISE
-80
-60
-40
-20
0
20
40
60
80
DEGREES ATDC

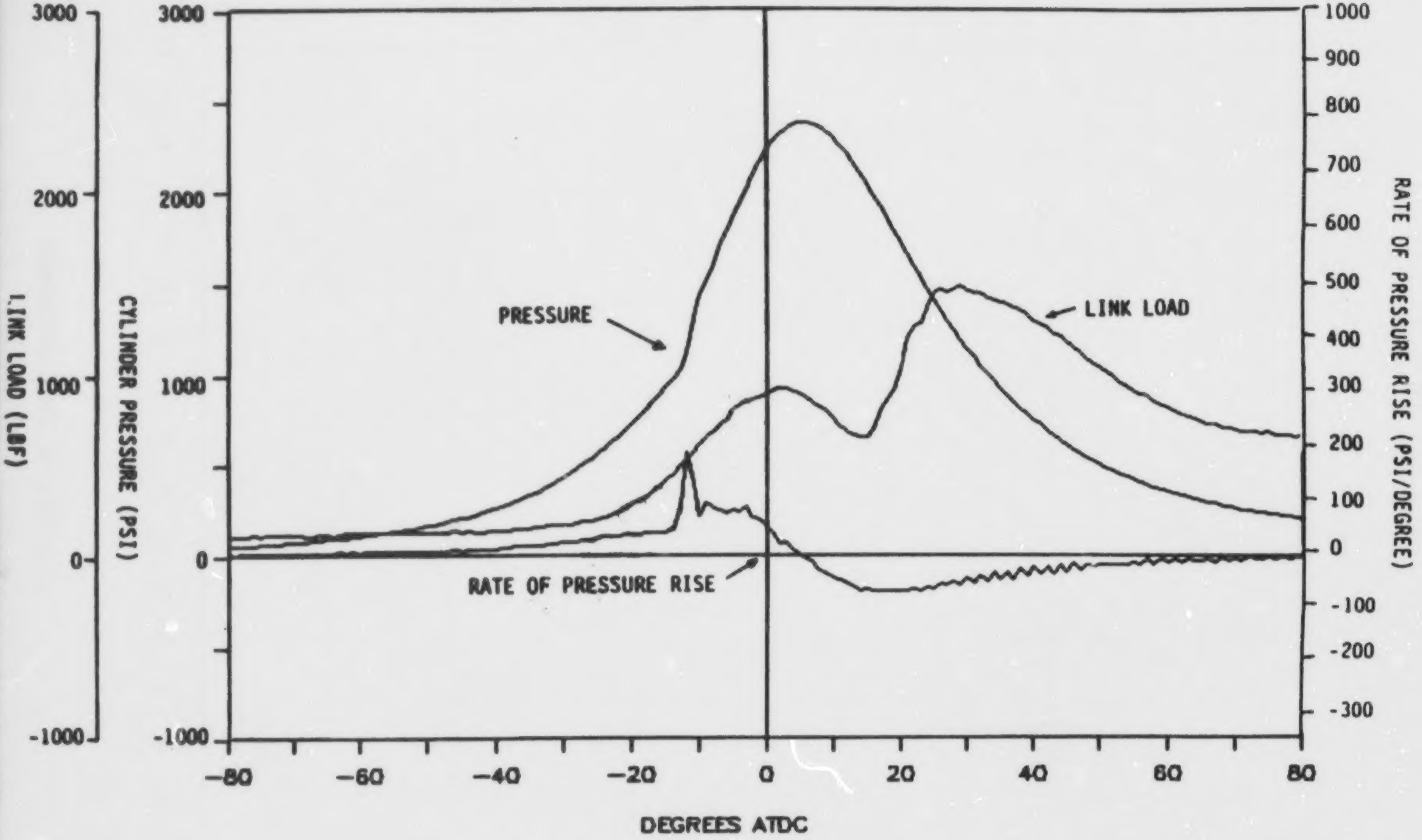
L10 COLD STARTS

% AVOCET BY VOLUME



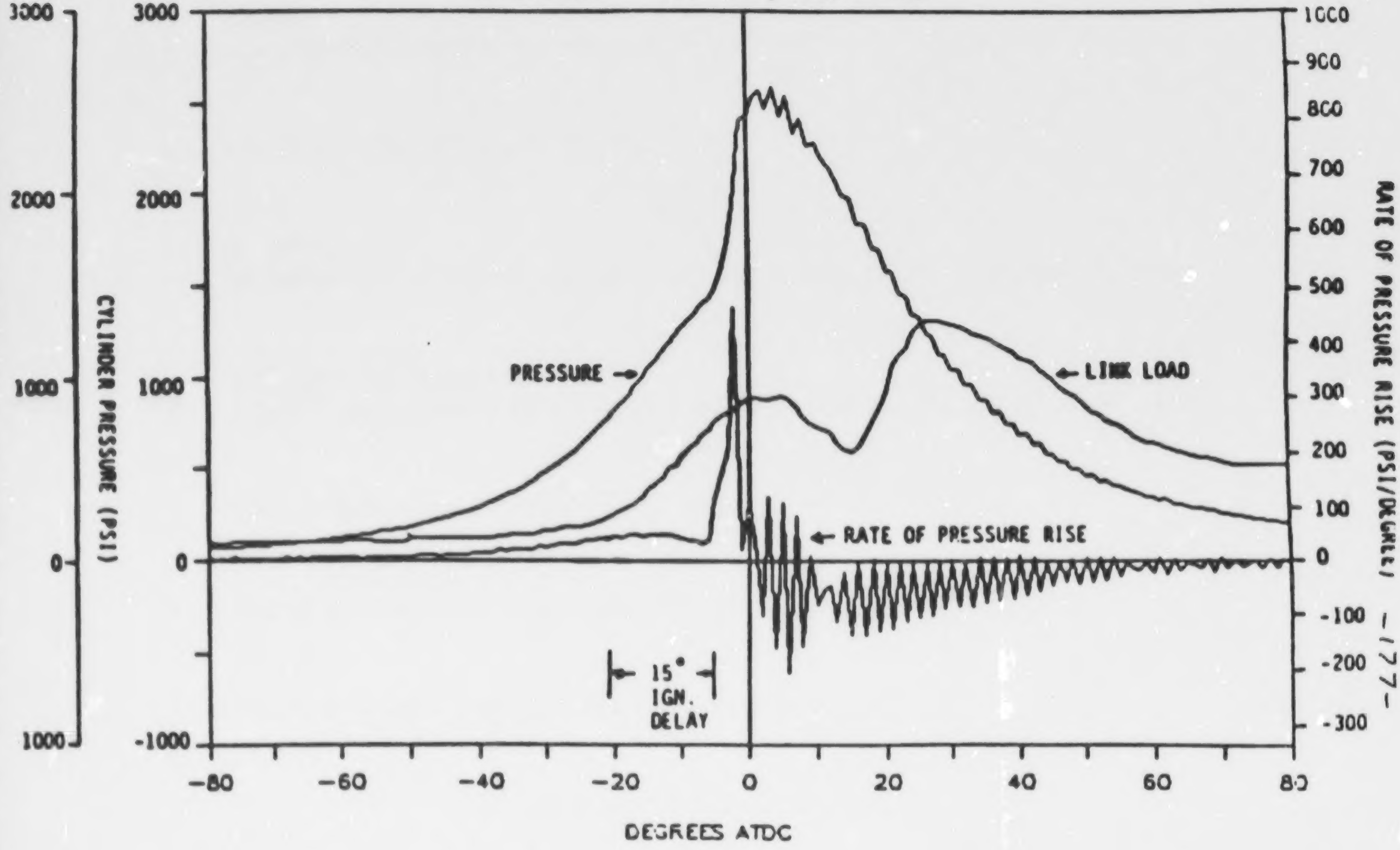
PRESSURE, DP/DT AND LINK LOAD

0.5% AVOCET – 1300 RPM/970 FT–LBF



PRESSURE, DP/DT AND LINK LOAD

PURE MEOH – 1300 RPM / 932 FT-LBF



METHANOL ENGINE STATUS/ISSUES

- EQUIVALENT POWER AND EFFICIENCY DEMONSTRATED
- DIESEL LIKE RATE OF COMBUSTION PRESSURE
- COLD STARTABILITY - EXCELLENT
- HYDROCARBONS REDUCED SIGNIFICANTLY BY INJECTION SYSTEM OPTIMIZATION. MOST ALDEHYDES AT IDLE/LIGHT LOAD
- OPTIMIZED ENGINE BUILD FOR TRANSIENT EMISSIONS TESTING. DURABILITY TESTS PLANNED
- FIELD TEST ENGINE IN VANCOUVER
- ADDITIVE ACCEPTANCE, DELIVERY LOGISTICS, FUEL SPEC AND COST ARE MAJOR ISSUES

PROJECT MILE - OPERATING RESULTS OF CANADIAN FLEET - TRUCK APPLICATIONS

M.A. Bol, L. King
Sypher:Mueller International Inc

NO PAPER AVAILABLE

DURABILITY OF DETROIT DIESEL METHANOL ENGINES

M. Jackson, S. Unnasch

Acurex

NO PAPER AVAILABLE

EVALUATION OF A LOW-COST RETROFIT OF A DIESEL TRANSIT BUS USING IGNITION IMPROVED METHANOL

JUNE 21, 1988

THOMAS J. TIMBARIO
EA-MUELLER, INC.

LAWRENCE R. HUDSON
NEW YORK STATE ENERGY
RESEARCH & DEVELOPMENT AUTHORITY

OBJECTIVES

- DEMONSTRATE THE OPERATION OF METHANOL DIESEL TRANSIT BUSES IN NEW YORK STATE.
- OBTAIN COMPARATIVE DATA ON OPERATION, MAINTENANCE, EMISSIONS AND COSTS (FOR BOTH DIESEL CONTROL AND METHANOL BUSES).

FOCUS

- CURRENT EFFORTS APPLIED TO EVALUATING LOW COST DIESEL ENGINE RETROFIT TO ALLOW USE OF METHANOL WITH CETANE IMPROVER ADDITIVE (AVOCET)
- IF FUNDING AND SCHEDULE PERMIT, PROGRAM MAY ALSO INCLUDE COMPARATIVE EVALUATION OF DDC METHANOL GLOW PLUG ENGINE(S).

CURRENT FLEETS

1. HUDSON GENERAL CORP., J.F. KENNEDY INTERNATIONAL AIRPORT
   - o GMC RTS II COACHES
   - o DDC 8V-71N ENGINES RETROFITTED TO OPERATE ON CETANE-IMPROVED METHANOL
     - 7% INITIAL AVOCET CONCENTRATION
     - HIGHER FLOW INJECTORS WITH METHANOL RESISTANT O-RINGS
     - HIGH VOLUME MECHANICAL FUEL PUMP WITH METHANOL RESISTANT SEALS
     - FUEL SYSTEM CALIBRATED TO ALLOW ENGINE TO DEVELOP WITHIN 10% OF DIESEL ENGINE REAR WHEEL HP (150 DIESEL, 164 METHANOL)
     - ELECTRIC PRIMING PUMP

2. NIAGARA FRONTIER TRANSIT AUTHORITY (METRO BUFFALO AREA)
   - ORION 40 FT. TRANSIT BUSES
   - DDC 6V92TA ENGINES RETROFITTED TO OPERATE ON CETANE-IMPROVED METHANOL
     - SAME BASIC MODIFICATIONS AS FOR 8V-71N ENGINES

CURRENT STATUS/RESULTS/PLANS

1. HUDSON GENERAL/JFK:
    - ONE BUS COMPLETED PRELIMINARY TRIAL EVALUATION
    - ENGINE TO BE REMOVED, PARTIALLY DISASSEMBLED AND INSPECTED FOR UNUSUAL WEAR
    - OPTIMIZATION/TESTING WORK TO REDUCE AVOCET CONTENT TO LOWEST PRACTICAL LEVEL.
    - COMPARATIVE EPA 13 MODE AND TRANSIENT EMISSION TESTS TO BE PERFORMED ON BOTH DIESEL AND OPTIMIZED METHANOL CONFIGURATIONS.
    - CHASSIS DYNAMOMETER EMISSION TESTS TO BE PERFORMED ON OPTIMIZED METHANOL CONFIGURATION
    - ENGINE/BUS RETURNED TO SERVICE FOR REMAINDER OF ON-ROAD EVALUATION (UP TO TWO YEARS).

- FUELING FACILITY DESIGN/SPECS COMPLETED. WAITING FOR RESOLUTION OF PROPERTY LEASE AGREEMENT ISSUES BETWEEN HUDSON GENERAL AND NY/NJ PORT AUTHORITY.
- PRELIMINARY SERVICE HISTORY DATA:
  - BEGAN SERVICE ON APRIL 12, 1988 WITH 146,000 MILES ON ENGINE/BUS.
  - COMPLETED PRELIMINARY SERVICE TRIAL ON JUNE 13, 1988.
  - ACCUMULATED 671 MI., 135 HOURS AND CONSUMED 738 GALLONS OF FUEL (0.91MPG), OVER 16 DAYS AT ABOUT 42 MI. PER DAY.
  - TYPICAL DIESEL FUEL CONSUMPTION IS 2-3 MPG.
  - AVERAGE SPEED OVER 2.3 MI LOOP IS 5 MPH.
  - OPERATIONAL PERFORMANCE HAS BEEN EXCELLENT WITH GOOD DRIVEABILITY AND ACCELERATION.
  - STARTING PROBLEMS HAVE OCCURRED DUE TO INSUFFICIENT TIME ALLOWED FOR PRIMING PUMP OPERATION (FIX TO BE INCORPORATED DURING ENGINE TESTING PHASE).

2. NFTA/BUFFALO

- FLEET OPERATING AGREEMENT IN PLACE.
- FUELING FACILITY DESIGN COMPLETED
- ENGINE RETROFIT WORK TO BE INITIATED OVER JULY/AUGUST 1988 IN COOPERATION WITH DDC.

EVALUATION OF A LOW-COST RETROFIT OF A DIESEL TRANSIT BUS USING IGNITION-IMPROVED METHANOL

ECONOMIC ASPECTS

Dr. Lawrence R. Hudson
New York State Energy Research
and Development Authority

SCENARIO: TRANSIT BUS OPERATORS WILL FACE TIGHTER FEDERAL AND STATE CLEAN AIR REGULATIONS IN 1990'S. IF METHANOL ENGINES ARE THE FIRST TO MEET THE REQUIREMENTS, THE BUS OPERATORS CAN:

- BUY NEW ENGINES FOR EXISTING BUSES;
- BUY NEW BUSES WITH NEW ENGINES; OR
- RETROFIT EXISTING ENGINES IN EXISTING BUSES.

QUESTION: WHAT IS MOST COST-EFFECTIVE?

METHANOL TRANSIT BUSES

SCENARIO OF IGNITION PROMOTER VERSUS NEAT FUEL APPROACHES

Ignition Promoter Added Cost per Gallon of Methanol		Neat Fuel Approaches Five Year Breakeven: Maximum Allowable Equivalent Added Cost			
PER GAL	PER YEAR[1]	Total	Capital[2]	Operation[3]	
				5 YR TOT	Annual
$0.30	$5,460	$27,300	$12,300	$15,000	$3,000
0.20	3,640	18,200	8,200	10,000	2,000
0.15	2,730	13,650	6,150	7,500	1,500
0.10	1,820	9,100	4,100	5,000	1,000
0.05	910	4,550	2,050	2,500	500
0.02	364	1,820	820	1,000	200

Notes

1. 18,200 gallons per year at 2.2 mpg in EPA Bus Cycle.
2. Engine cost. Added cost for bus fuel tanks, etc. assumed equal.
3. Includes downtime. Neat fuel engines are assumed to require replacements of spark/glow plugs.

2-3. Combinations shown are arbitrary.

Table 1
Capital Costs of Methanol Transit Buses
Estimated Incremental Capital Cost vs. Conventional Diesel

I Engine Source	II Engine Type and Ignition Approach	III Engine	IV Rest of Vehicle[1]	V Total
Detroit Diesel Corp. (DDC)	6V-92TA 2-stroke Glow Plug	\$ 1,000[2]	\$ 1,500	\$ 2,500
M.A.N.	D2566FMUH 4-stroke Spark Plug	1,000[3]	7,000	8,000[4]
Cummins	L-10 4-stroke Ignition Promoter (IP)[5]	500[6]	1,500	2,000
Field Retrofit DDC	8V-71 2-stroke IP[7]	500[8]	1,500	2,000

Notes

1. Assumed new or retrofit engine installed in existing bus configured for same engine family. Replace fuel tank, fuel lines, install cooler and/or additional fuel pump.
2. \$500 to \$1,500 at production volumes. DDC informal estimate, May 1988.
3. Assumed equal to DDC at similar volume.
4. Sold as vehicle unit only, at \$24,000 more than comparable conventional bus. Assumed to drop to one third at production levels.
5. Avocet or similar additive.
6. Assumed for production volumes. Cummins informal estimate 1987.
7. Change to larger injectors and modified fuel-wetted materials (including fuel filter). Conclusions believed broadly applicable also to 6V-92.
8. For fifth and subsequent units. Engine costs lower if retrofitted at overhaul.

TABLE 2

OPERATING COSTS OF METHANOL TRANSIT BUSES

I	II	III	IV	V	VI
	ESTIMATED INCREMENTAL ANNUAL OPERATING COST VS. LOWEST METHANOL				
ENGINE SOURCE	TOTAL ANNUAL METHANOL FUEL[1]	MAINTENANCE	FUEL	DOWNTIME	TOTAL
DDC	$15,450	$3,800[2]	ZERO	$ 200[3]	$ 4,000
M.A.N.	15,450	2,800[4]	ZERO	200	3,000
CUMMINS	$15,450	ZERO[5]	ZERO	ZERO[6]	ZERO
FIELD RETROFIT	17,000[7]	ZERO[8]	1,550	ZERO[8]	1,550

NOTES

1. FUEL CONSUMPTION IS ASSUMED TO BE ABOUT EQUAL (2.2 M.P.G.) AMONG WELL-EVOLVED FACTORY-BUILT ENGINES AND SLIGHTLY LOWER (2.0 M.P.G.) FOR FIELD RETROFITS. ESTIMATED FOR EPA BUS CYCLE, 40,000 MILES PER YEAR, AND $0.85 PER GALLON (SPOT MARKET U.S. GULF COAST 5/12/88).
2. INJECTOR LIFE IN PHASE I CANADIAN BUSES IS NOW 500-600 HOURS. DDC NEAR-TERM GOAL IS 1,000 HOURS. IF ACHIEVED, NEED INJECTORS REPLACED/REBUILT TWICE EACH YEAR ($1,800 PER CHANGE). ALSO EXPECT GLOW PLUG RELIABILITY TO IMPROVE TO ONE FAILURE PER YEAR ($200). OTHER COMPONENTS (BYPASS ACTUATOR, GLOW PLUG CONTROLLER) EXPECTED TO BE FULLY RELIABLE.
3. LARGE BUS FLEETS MAY HAVE ADEQUATE RESERVE CAPACITY. SMALL FLEETS MAY EXPERIENCE REVENUE LOSS ESTIMATED HERE AS RESULT OF LARGER MAINTENANCE REQUIREMENT.
4. BASED ON M.A.N. GOAL OF 10,000 MILES OF SPARK PLUG OPERATION IN BUS CYCLE (PRESENT LIFE IS 3,000 MILES) @ $25/PLUG AND $100 LABOR, 4 TIMES PER YEAR, AND REPLACEMENT OF ONE SET OF INJECTORS PER YEAR @ $1,800.
5. LONG MAINTENANCE INTERVALS EXPECTED AS WITH CONVENTIONAL DIESELS, BASED ON VERY LIMITED DATA.
6. ESTIMATED FOR TRANSIT BUS SERVICE BASED ON LIMITED DATA FROM CANADIAN TRUCK EXPERIENCE.
7. BASED ON 2.0 M.P.G. EPA BUS CYCLE EQUIVALENT, BELIEVED ACHIEVABLE IN JFK TEST BUS.
8. LONG MAINTENANCE INTERVALS EXPECTED AS WITH CONVENTIONAL DIESELS, BASED ON VERY LIMITED DATA.

TABLE 3

COMPARISON OF CAPITAL AND OPERATING COSTS FOR METHANOL TRANSIT BUSES

ENGINE SOURCE	INCREMENTAL COST		DIFFERENCE IN INCREMENTAL COST (VS. LOWEST METHANOL)		INCREMENTAL COST ($/GAL)[3] FOR IGNITION PROMOTER			
	CAPITAL[1] I	OPERATION[2] II	CAPITAL III	OPERATION IV	@$0.20	0.15	0.10	0.05
DDC	$ 2,500	$ 4,000	500	4,000	--	--	--	--
M.A.N.	8,000	3,000	6,000	3,000	--	--	--	--
CUMMINS	2,000	ZERO	--	--	3,650	2,750	1,800	900
FIELD RETROFIT	2,000	1,550	--	1,550	4,000	3,000	2,000	1,000

NOTES

1. FROM COLUMN V OF TABLE 1.
2. FROM COLUMN VI OF TABLE 2. EXCLUSIVE OF IGNITION PROMOTER.
3. TO NEAREST $50. ASSUMED 18,200 GAL PER YEAR FOR CUMMINS, 20,000 GAL PER YEAR FOR RETROFIT.

TABLE 4

ALLOWABLE COST FOR IGNITION PROMOTER FOR METHANOL TRANSIT BUSES

ENGINE	DIFFERENCE IN INCREMENTAL COST (VS. LOWEST METHANOL)						MAXIMUM ALLOWABLE ADDED COST PER FINISHED GALLON OF IGNITION PROMOTER AT 5-YEAR PAYBACK[1]	
	CAPITAL		ANNUAL OPERATION		5-YEAR OPERATION			
SOURCE	VS. CU	VS. RT	VS. CU	VS. RT	VS. CU	VS. RT	VS. CU	VS. RT[2]
DDC	$ 500[3]	$ 500[3]	$4,000[4]	$2,450[5]	$20,000	$12,250	$0.23	$0.13
M.A.N.	6,000[3]	6,000[3]	3,000[4]	1,450[5]	15,000	7,250	0.23	0.13

NOTES:

1. ASSUMES 91,000 GALLONS OF FUEL OVER 5 YEARS FOR CUMMINS, AND 100,000 GALLONS FOR RETROFIT, EQUATED TO INCREMENTAL CAPITAL AND 5-YEAR OPERATION COST FOR DDC AND M.A.N.
2. ASSUMES EQUAL CONCENTRATION OF IP IN NEW CUMMINS AND FIELD RETROFIT ENGINES. CONCENTRATIONS MAY DIFFER DUE TO FACTORY ABILITY TO ALTER COMPRESSION RATIO AND OTHER FACTORS.
3. FROM COLUMN III OF TABLE 3.
4. FROM COLUMN IV OF TABLE 3.
5. CALCULATED FROM COLUMN IV OF TABLE 3.

PROJECT MILE - OPERATING RESULTS OF CANADIAN FLEET - BUS APPLICATIONS

M. Bol, L. King

Sypher:Mueller International Inc

NO PAPER AVAILABLE

- 195 -

DEVELOPMENT AND DEMONSTRATION OF AN AUTOMATED TRAP SYSTEM FOR A NEW YORK CITY BUS

K. Ha
J.A Larocque
Ontario Research Foundation

F. Strnisa
New York State Energy, Research & Development Authority

June 1988

DEVELOPMENT AND DEMONSTRATION OF AN AUTOMATED TRAP SYSTEM FOR A NEW YORK CITY BUS

Project Coordinator and Prime Contractor:

Ontario Research Foundation
Advanced Engine Technology
(Mr. Kong Ha Manager, Emissions)

Project Sponsored by:

New York State Energy, Research & Development Authority
(Dr. F. Strnisa)

With the support of:

New York City Transit Authority
(Mr. Barry Washington)

New York City Dept. of Environmental Protection
(Mr. Laslow Goldberger)

Corning Glass Works
(Mr. Jim Gibson)

Donaldson Company Inc.
(Mr. Julian Imes)

Engelhard Corporation
(Dr. Ken Jagel)

ABSTRACT

A fully automated system has been developed which will reduce total particulate emissions from a typical 6V-92TA transit coach engine by over 70 percent and eliminate visible black smoke.

Fuel consumption increases of under 6 percent were measured during a 100 hour system durability test while operating the engine over the New York City transient bus cycle.

The system has been installed on a GM RTS 04 transit coach and will be operated by the New York City Transit Authority for a period of 1 year. System durability and engine emissions will be monitored.

NEW YORK CITY BUS TRAP SYSTEM

OBJECTIVES:

- Eliminate visible black smoke
- Reduce total particulate emission by 70%
- Demonstrate system durability in a 1 year field trial

DESIGN CRITERIA:

- Very limited space available (GM RTS 04 coach).
- DDC 6V92TA engine - high exhaust flow, low exhaust temperature.
- Large union operation - manual operation and training difficult.
- Low sulphur fuel - can use active catalyst.
- New York City cycle - used by NYC DEP to measure emissions.
- Fire safety, liability concern.

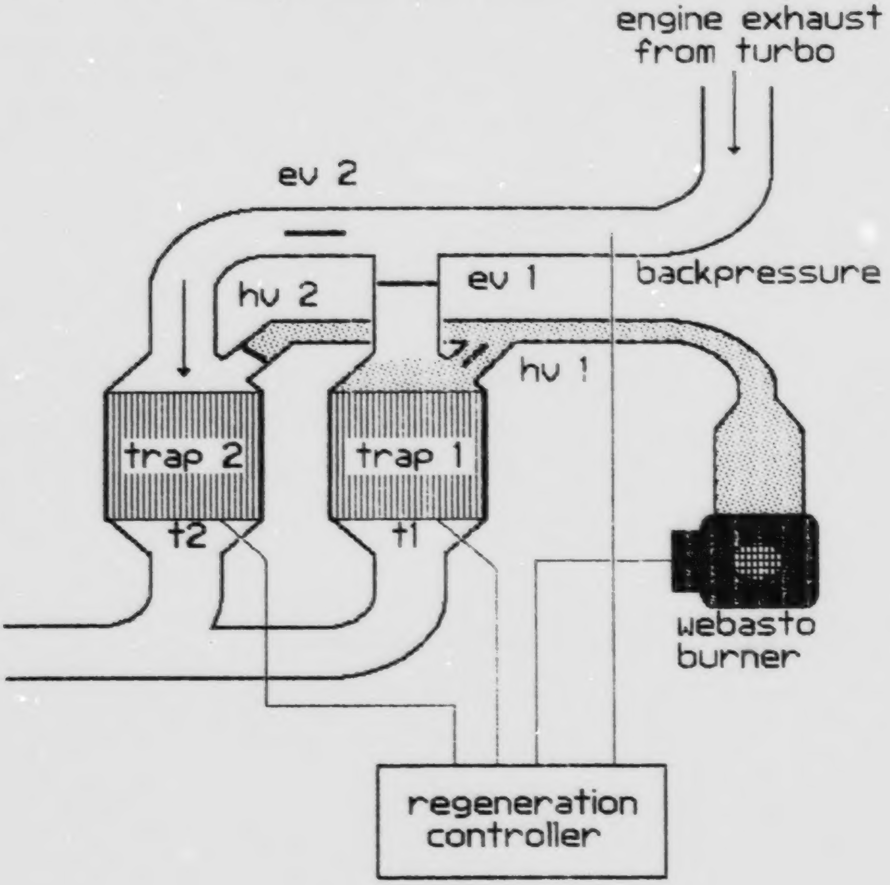
CONTROL DEVELOPMENT:

- Monitor trap temperatures
- Ensure acceptable thermal stress during regeneration
    - radial <125°C/in
    - axial <250°C/in
- Monitor exhaust backpressure
- Ensure acceptable backpressure throughout operation (< 4 in Hg maximum)
- Minimize fuel consumption

MAJOR COMPONENTS:

- 2 Traps: Corning EX 66/17/100
  Engelhard Catalyst
  Donaldson Canning
- 4 Valves and Actuators
- Diesel Fuel Burner
- Electronic Controller
  - programmable
  - controls all valves
  - monitors 2 trap face temperatures
  - controls burner
  - controls blower
  - contains counters

NEW YORK CITY BUS TRAP SYSTEM


engine exhaust
from turbo
ev 2
hv 2
ev 1
backpressure
hv 1
trap 2
trap 1
t2
t1
webasto
burner
regeneration
controller

OPERATION SEQUENCE:

- After engine startup, exhaust is routed through both traps for 15 minutes to pre-heat the ceramic substrates, and minimize thermal stress.

- The trap regeneration cycle begins as follows:
  - the traps associated exhaust valve is closed and the heat valve opened;
  - the burner and blower are started;
  - the burner operates for 9 minutes or until the trap face temperature reaches approximately 675°C;
  - the burner extinguishes and the blower continues to operate for an additional period of approximately 5 minutes;
  - the blower stops and the heat valve closes;
  - the exhaust valve remains closed for the remainder of the other trap's loading cycle (approximately 16 minutes);
  - the 30 minute cycle repeats automatically, regenerating and loading each trap on alternate cycles.

FAIL SAFE DESIGN

- Both exhaust valves are held open by coil springs. Pneumatic actuators are used to drive the valves closed during trap regeneration. In the event of a loss of air pressure or electrical power to the controller, both exhaust valves will open immediately. The engine exhaust will flow through both traps, reducing the backpressure.

- Trap temperature and exhaust backpressure are constantly monitored by the regeneration controller. If:

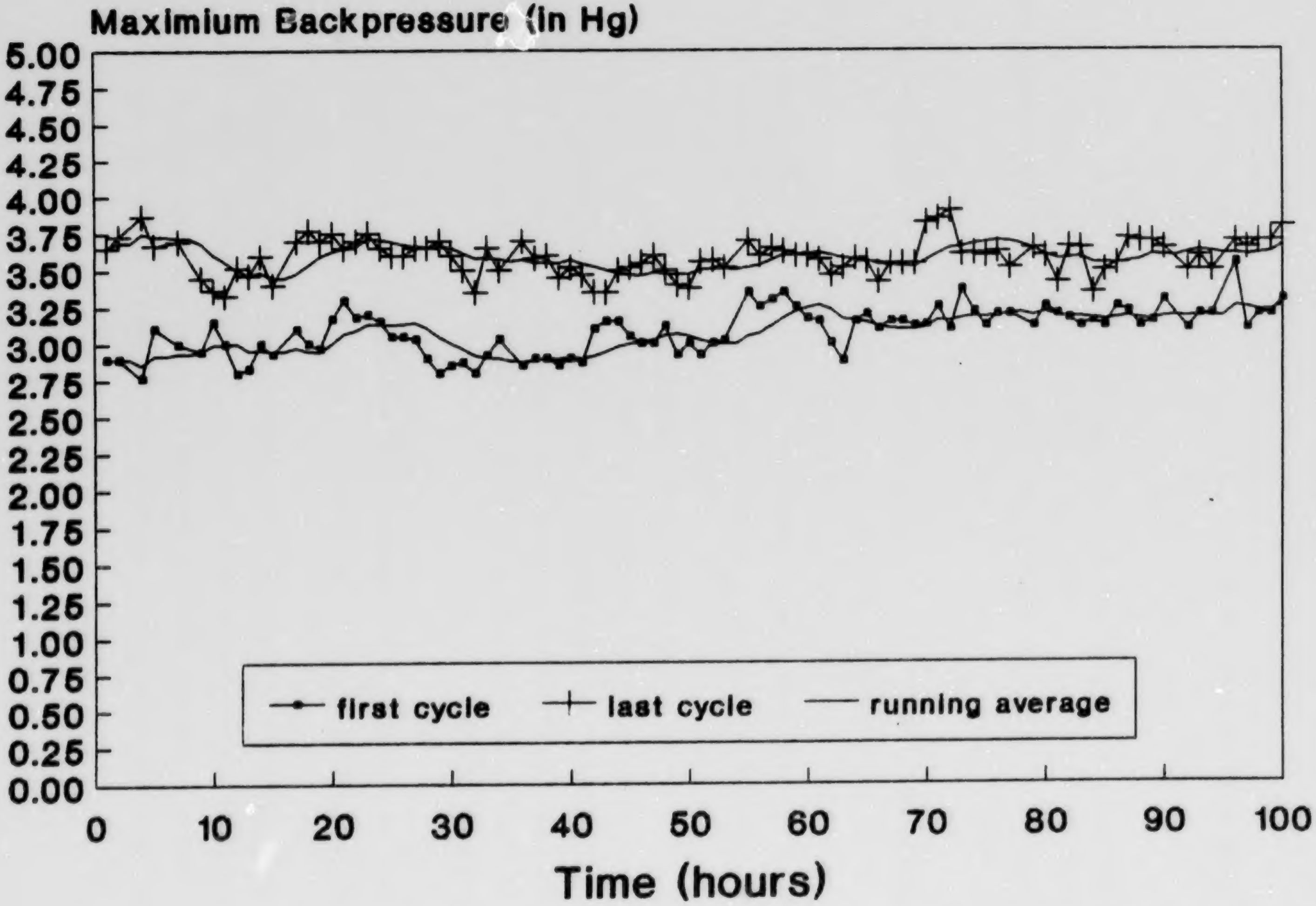
  trap temperature > 900°C or
  exhaust backpressure > 8 inches Hg

  the system enters its fail safe mode:

  - the burner and blower are locked out and power is disabled;
  - both exhaust valves open;
  - both heat valves close;
  - an indicator lamp on the regeneration controller is lit.

Operation of the regeneration system is inhibited until appropriate maintenance has been performed.

New York City Bus Trap System



March 1988

TRAP SYSTEM TESTING

Maximum backpressure was monitored during 100 hours of testing of the trap system in a computerized test cell at ORF. The New York City transient bus cycle was used during the test.

Maximum 'first cycle' backpressure, measured during the cycle immediately following trap regeneration, is an indicator of how well the trap regenerated. Maximum 'last cycle' backpressure, measured during the final cycle prior to regeneration, is an indicator of trap loading.

The 'running average' more clearly shows the trends of the backpressures during the 100 hour testing. The consistency of the running average of the maximum backpressures indicates that the traps are returning to their 'clean' state after each regeneration and are not retaining particulates.

Maximum trap backpressure did not exceed 4.5 inches Hg on either trap.

No component failures were experienced during the test. Thermal stresses on the trap substrates were below design limits. Burner fuel consumption was approximately 6 percent of the fuel consumed by the engine during the test.

REGENERATION EMISSIONS USING AN IN-LINE DIESEL BURNER

	Baseline	With Trap	+ Regeneration
HC	100%	-14%	-10%
NO_x	100%	-6%	-5%
CO	100%	-10%	-3%
Part.	100%	-92%	-90%

Engine emission reductions are shown. Taking the baseline diesel emissions as 100%, particulate emission reductions with the EX66 traps of 92% were measured. Including trap regeneration, particulate emission reductions of 90% were measured. Small reductions in HC, CO, and NO_x were also measured.

SYSTEM INSTALLATION:

- Will not interfere with regular engine servicing.
- All pipes will be insulated.
- All surface temperatures within safety specifications.
- 1 coolant pipe retrofitted.
- 1 oil filter relocated
- Regeneration controller installed inside the battery compartment.

RESULTS TO DATE:

(95 hours)

- Thermal stresses within limit
- Exhaust backpressure within limit
- No component failures
- No visible black smoke

DYNAMOMETER EVALUATION OF THE FORD FLEXIBLE FUELLED VEHICLE

D. Elliott, T. Topaloglu
Ontario Ministry of Transportation

NO PAPER AVAILABLE

OPTIMIZATION OF COMPRESSION RATIO FOR A 2.5L PROPANE FUELLED ENGINE

J. Lanigan, R. Motta
Chrysler Canada Inc

NO PAPER AVAILABLE

THE POTENTIAL FOR GASEOUS FUEL INJECTION SYSTEMS (GFI) IN RETROFITTING NATURAL GAS & PROPANE VEHICLES

Ontario Research Foundation
Stephen A. Carter

Ontario Research Foundation (ORF), with assistance from the Canadian Gas Association (CGA) and the Ontario Ministry of Energy, has formed an Automotive Controls Technology group (A.C.T.). That group evaluated the alternative fuels market and existing product technologies. The findings from that study are presented in this paper.

During the course of the paper I will highlight a computer based fuelling system that ORF has proposed, and which CGA has contracted to develop to a commercial state for NGV applications.

As an introduction, it is appropriate to define the potential size of the U.S. and Canadian markets. Those two markets total 178 million vehicles, comprised as follows:

	United States	Canada
Passenger Cars	117,268,000	14,266,600
Trucks	44,825,000	1,511,000
SUB-TOTAL:	162,093,000	15,777,600
	177,870,600	

That is the upside, the largest that the market could ever be. The downside is also well known, and includes a number of factors which make the likely market much smaller than 178 million vehicles. Those factors include: conversion system availability and cost; alternative fuel availability and cost; alternate fuel system range and performance; customer awareness and acceptance of alternate fuels.

Another challenge that exists in the market...which is the aftermarket...is the diversity of the fleet. There are over 25 companies producing and offering cars for sale in the two countries. Additionally, each of the manufacturers tend to have a relatively large number of distinct engines (from 3 to 15 each), which change from model year to model year. Finally, the cars tend to stay in service for a long time (for example, covering 50% of the in-service fleet would require having technology for the past 7 model years). The following table quantifies these points:

	U.S.A.	CANADA
Car companies (in 1986)	26	29
Engines in 1986 (90% of sales)	41	48
Age of in-service vehicles (years)		
50% of fleet	0-7	?
66% of fleet	0-9+	?
75% of fleet	0-11-	?
90% of fleet	0-15	?

Every model year has a staggering proliferation of companies, vehicles and engines. Moreover, no one company or engine dominates the market. Our conclusion is that while there is an enormous market potential, it is only attainable with a universal system. In this case, a universal system is conceived as one that works on: natural gas and propane; gasoline and diesel type engines; aftermarket and OEM applications.

Without a universal fuelling system, it is felt that alternative transportation fuels (ATF's) are doomed to a small and ever-dwindling market niche. Accordingly, ORF has conceived and proposed a universal Gaseous Fuel Injection (GFI) system.

The key word in that description was universal. Universal translates into only ONE kit to perfect, build, stock and install. It also translates into the least engineering overhead to support the product in production and to develop new applications.

Key points regarding ORF's GFI system are highlighted below:

Universal (one fits all)
Computer based
Installer adjusted
Adaptive memory (kept alive)

NGV = sonic metering
LPG = sub-sonic metering

The universal concept provides for the same kit working on all vehicles: whether new or old; whether 4, 6 or 8 cylinder; whether carbureted or fuel injected; whether foreign or domestic. The selection of a computer to control the system allows the system to correct for a wide range of variables, including: car to car variations; vehicle ageing; temperature and pressure changes; fuel composition changes; and control system errors (whether hardware or software). The installer adjustment feature specifically eliminates the scenario of installers waiting on the factory for more stock or for new calibrations. The non-volatile adaptive memory ensures that the correction factors that the system is continually updating are kept alive for the life of the car.

It is worthwhile to focus for a moment on the metering selections chosen. NGV will use a sonic metering valve, which is the simplest to model and control. The propane (or LPG) version will use a sub-sonic metering valve, which is necessary for the system to be able to function properly at low ambient temperatures where propane's vapour pressure is too low to provide sonic operation.

The GFI system is comprised of the following building blocks, or physical pieces:

Regulator
Metering valve
Nozzle
Computer
Wiring harness
Standalone sensors
Integrated sensors
Fuel selector switch

The regulator provides the metering valve with gaseous fuel at a constant pressure. The NGV regulator is a single stage regulator, while the LPG vapourizer/regulator is a 2-stage device. The NGV regulator will provide gas in the range of 30 - 100 PSIG, while the LPG regulator will regulate to roughly 3 PSIG. As noted previously, the NGV metering valve is sonic, while the LPG version is sub-sonic. The nozzle is installed in the intake air stream above the throttles and provides for proper mixture of the air and fuel. The computer is unchanged between NGV and LPG versions, except for the data entered into the software. The wiring harness connects the computer, sensors and metering valve and also ties the system into the car's existing electrical system.

With one exception, the system does not use information from the car's sensors. The one exception is oxygen sensor data, which is taken from the car's oxygen sensor if it has one. Otherwise, the GFI system uses its own separate sensor network to gather the information that it needs. That information is gathered from both standalone sensors (which must be attached by the installer) and from integrated sensors, which are imbedded in the regulator or metering valve.

Finally, for dual fuel applications, there is a fuel selector switch to permit the vehicle to switch back and forth between gasoline and the ATF.

Schematically, the system appears as shown in Fig. #1.

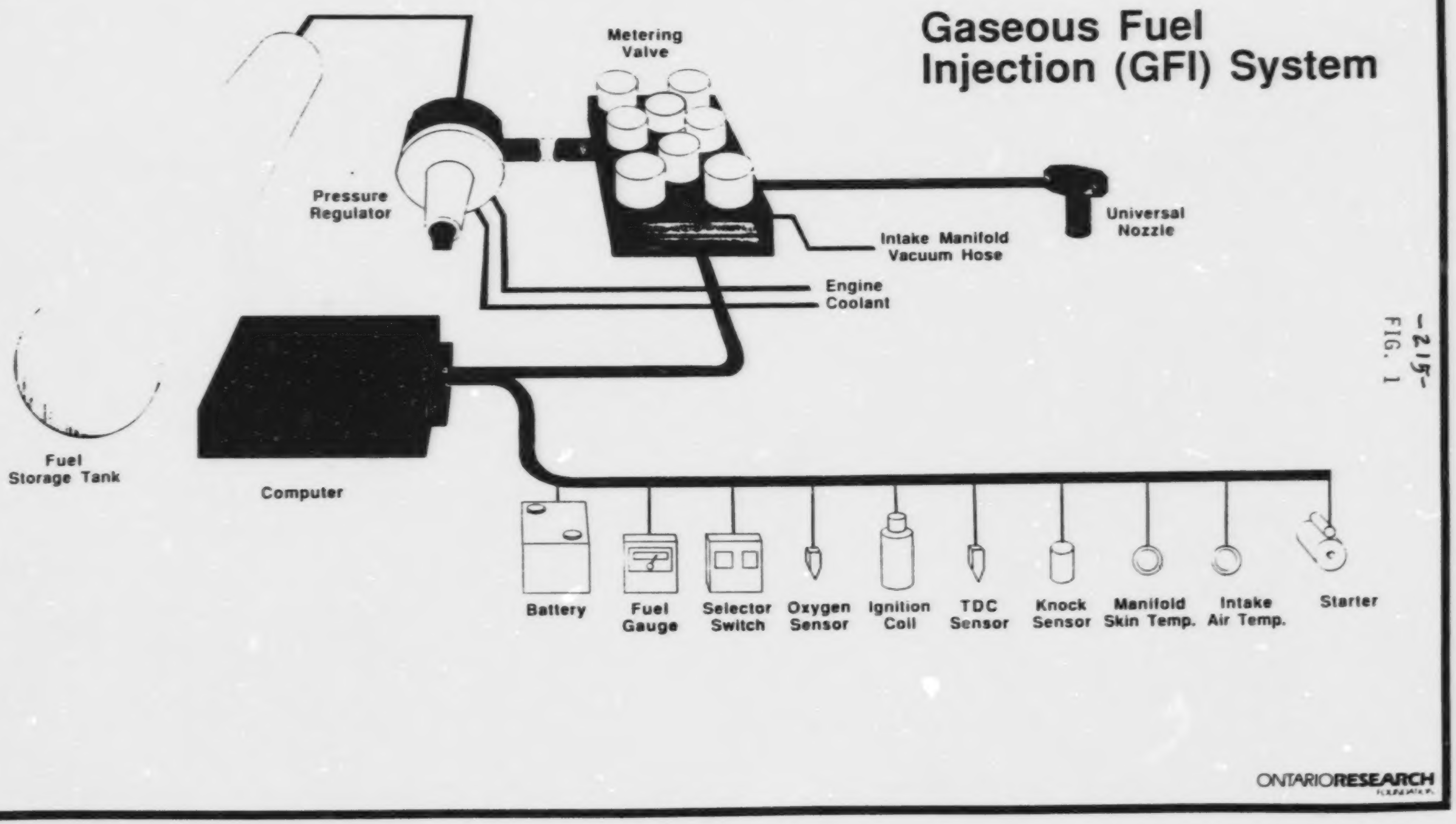

Gaseous Fuel Injection (GFI) System
Metering Valve
Pressure Regulator
Universal Nozzle
Intake Manifold Vacuum Hose
Engine Coolant
Fuel Storage Tank
Computer
Battery
Fuel Gauge
Selector Switch
Oxygen Sensor
Ignition Coil
TDC Sensor
Knock Sensor
Manifold Skin Temp.
Intake Air Temp.
Starter
ONTARIORESEARCH

FIG. 1

FIG. 1

Perhaps the most important point to garner from the schematic is that the computer is conceived to be an underhood device. That location is deemed mandatory for the system to be practical in the aftermarket. The alternative of placing the computer in the passenger compartment or trunk puts unrealistic burdens on the installer (1. to properly pierce and reseal the body where the harness passes through, and 2. to find real estate to accept the computer behind the dashboard, kickpanels or seats); and an unattractive financial penalty on the harness (i.e. easily 500 to 1000 extra feet of wire in the harness).

In terms of complexity, the GFI system makes all of the same interconnections with the vehicle as the current ATF hardware, plus it adds two temperature sensors, while having a universal nozzle that is much quicker and simpler to install than a mixer. Thus, the GFI system should be quicker and cheaper to install.

The actual installation process consists of the following phases:

1. Install the system
2. Enter engine data into the computer* (this step could be done by the factory if the kit were ordered to "fit" a specific engine)
3. Operate the engine briefly with the computer in the learn mode (this allows the adaptive memory to fine tune the "coarse" calibration that was automatically created by Step 2).

* Note: The engine data to be entered includes:

DISPLACEMENT
NO. CYLINDERS
BORE DIAMETER
COMP. RATIO
NO. INTAKE VALVES
THERMOSTAT TEMP.
IDLE RPM
PEAK TORQUE LEVEL
PEAK TORQUE RPM
PEAK POWER LEVEL
PEAK POWER RPM
NOMINAL AIR:FUEL RATIO
FUEL DENSITY
INTAKE MANIFOLD STYLE

This data is the key information that allows the computer's software to develop a universal calibration which matches a specific engine. In order for this scheme to be viable, a few conceptual breakthroughs were needed. Those breakthroughs included:

re Speed-Density calculation of Intake air flow	Volumetric efficiency modelling Intake-air heat transfer modelling EGR flow compensation modelling
re Oxygen sensor Feedback loops	Transport delay periods for engines Loop stability limits.

The theoretical characterization of volumetric efficiency of an engine based on engines parameters was a major breakthrough in that it permitted the modelling of engines without testing them. The modelling of intake air heat transfer reduced a significant source of error in speed density systems. Finally, the selection of a scheme to compensate for EGR flow rate was a critical factor in further reducing a source of speed density errors.

Having made these advances, there is still a clear need to rely on some calibration means of refining the "coarse" universal calibration that could be calculated. An oxygen sensor loop is the obvious tool to minimize the time needed to null out errors in the universal calibration.

The following table shows test results in an engine using the "coarse" universal calibration values. The data shown is actual metering values (expressed as Lambda) vs manifold absolute pressure and RPM. The average Lambda value across all speeds and loads was off by 4.5% from the ideal level of 1.0. The largest single errors were +7% and -9%. When driving on the Hot 505 portion of the chassis dyno emissions test cycle, the average metering was off by 2%. Thus, the universal system is felt to provide "coarse" values which are close enough to allow the adaptive memory to correct and provide a pleasing vehicle.

λ- VALUES OBTAINED WITHIN VOLUMETRIC EFFICIENCY TABLES

1.8L 4 CYL

MAP ("Hg)	1	2	3	4	5	6	7	8	9	10
29.6			0.99	1.03	1.04	1.06	1.06	1.05	1.07	
25.0		1.00	0.98	0.98	1.00	1.02	1.03	1.02		
21.0		1.00	0.97	0.94	0.95	0.95	0.98	0.96		
18.0	1.02	1.02	0.97	0.94	0.95	0.94	0.94	0.94		
15.0		1.02	0.97	0.96	0.92	0.92	0.94	0.93		
13.0		1.05	1.00	0.98	0.94	0.92	0.92	0.93		
9.0			1.15	1.05	0.97	0.95	0.91	0.92		
	700	2039	1543	2290	3400	3917	4573	5200	5720	6240

RPM

AVG. λ* = 0.98 AVG. ABSOLUTE FUELING ERROR * = 0.045

A similar table is provided for a 2.5L 4 cyl engine. This engine had an average error across all speeds and loads of 4.3%.

λ- VALUES OBTAINED WITHIN VOLUMETRIC EFFICIENCY TABLES

2.5L 4 CYL

MAP ("Hg)	1	2	3	4	5	6	7	8	9	10
29.6										
25.0					0.98	1.02				
21.0				0.94	0.96	1.00	1.03			
18.0				0.92	0.95	0.98	1.00	1.06		
15.0			0.92	0.92	0.93	0.95	0.99	1.02		
13.0		0.92			0.93	0.96	0.97	1.00		
9.0		0.90	0.90	0.92	0.96	0.98	1.00	1.00	1.05	
	700	972	1349	1873	2600	3098	3692	4400	4840	5280

RPM

AVG. λ = 0.97 AVG. ABSOLUTE FUELING ERROR = 0.043

Finally, I would like to mention the need for EGR compensation in a speed density system. As the speed density system infers mass air flow into the engine, it must make some assumptions as to the composition of the intake charge. Specifically, it must assume what portion of the charge is: nitrogen, oxygen, fuel, exhaust gas (EGR). If the assumptions are wrong, then the engine will be misfuelled. For example, if the intake charge were 10% EGR and the program assumed 0%, the program would calculate 111% of the actual oxygen content to be available, and thus overfuel the engine by 11%.

The metering errors that can exist by mistakes in EGR assumptions are highlighted in the following chart. That chart shows percent time at the metering was: 0.97 < Lambda < 1.03, when the car was driven on the chassis dynamometer emissions driving cycle. This particular chart was for a propane fuelled car operating on a GFI type system.

λ - DISTRIB. (FTP 75)

		T WHERE .97≤ λ ≤1.03
GASOLINE	C1372	67%
GASOLINE	H505	66%
PROPANE	C1372	82%
(- EGR)	H505	78%
PROPANE	C1372	68%
(+ EGR)	H505	71%

The data shown are for both the hot and cold portions of the test (C1372 denotes the cold 1372 portion of the test, H505 denotes the hot 505 second portion of the test.) Note that when the engine was run on propane and EGR was turned on (but not compensated for in the program), the time that the metering was within the 3% window dropped from 78 - 82% to 68 - 71%, a significant loss in metering accuracy.

This, then, defines the system that CGA has funded to develop to a commercial state for gasoline engines. The working approach is to develop the system in three modules: core, gasoline, diesel. The core work provides hardware that is universal to all engines and applications. The gasoline and diesel modules provide hardware and software that are unique to their specific engine type. The contents of these modules are shown as follows:

GFI DEVELOPMENT MODULES

CORE	· COMPUTER · METERING VALVE · REGULATOR · SELECTOR SWITCH · FUEL NOZZLE
GASOLINE	· SOFTWARE · WIRING HARNESS · TEMPERATURE SENSORS
DIESEL	· SOFTWARE · HARDWARE (NOZZLE, SENSORS, IGNITION SYSTEM COMPONENTS) · CALIBRATION · MAPPING & ADAPTATION

To date, CGA has funded the work on the core and gasoline modules. We are still seeking funding for the diesel work. Additionally, we are seeking funding from the Canadian Auto Propane Council to develop a similar system for propane fuel.

Notably, the application of this system to diesel type engines is at an earlier developmental stage. We are assuming that any such applications will have the engine converted to an OTTO cycle arrangement (i.e. throttled and sparked). Thus, a significant amount of engine specific work will need to be done on each engine to assure that the proper fuel and spark strategies have been implemented to achieve the necessary goals for emission, fuel economy, power output and engine reliability/ durability.

In summary, when we review the GFI System's potential, we conclude that:

GFI Technology - outstanding

Vehicle Tolerance - marginal

Marginal Issues - diagnostics
- adaptive memory

That is, while the systems are predicted to work very well, the acceptance of the system by the gasoline computer's diagnostics and adaptive memory system is marginal. Two problem areas exist and need attention.

Firstly, the on-board diagnostics were developed solely for gasoline operation. When the car is run on an ATF, the diagnostics may disapprove of the ATF's characteristics (i.e. knock characteristic of 130 octane NGV) and conclude that something is seriously wrong. The result may be a lit "check engine" light on the dashboard, or compromised driveability if the system invokes a "limp home" or default program. In almost all scenarios, this situation is unnecessary and exists only because the OEM's diagnostics were not written to recognize and accept operation on an alternate fuel. The result is unnecessary inconvenience and expense to the vehicle operator.

The second problem area is adaptive memory. The OEM computers very commonly have a non-volatile memory that is continually correcting the metering based on an oxygen sensor signal. When the vehicle is run on an ATF, the computer continues to operate its adaptive memory, assuming that the car is still on gasoline. In fact, it "mislearns" a correction factor for the ATF and subsequently will likely drive poorly for a while when switched back to gasoline (i.e. until it relearns the proper correction factors for gasoline). This temporary inconvenience is also unnecessary.

Both of these conditions irritate the consumer for no purpose. The solution is not to develop better electronic "band aids", which fool the OEM computers; it is instead to get the OEM's to revise their computers so that they can recognize and accept ATF useage. We propose the universal adoption of a Diagnostics Inhibit Protocol (DIP) wherein OEM's computers would have an input port that could be energized to signal that an ATF was being used and which would cause them to inhibit their diagnostics and adaptive memory routines.

DIAGNOSTICS INHIBIT PORT (DIP)

DIP = INHIBIT DIAGNOSTICS & MEMORY
(DURING ALTERNATE FUEL MODE)

SHUT-OFF INJECTORS
(IE NON EMISSIONS TAMPERING)

DIP ELIMINATES AN NGV/LPG FUEL ROADBLOCK

This DIP protocol is seen as a necessary step in making ATF's legitimate in North America.

In conclusion, we see the U.S. and Canadian fleet as a 178 million vehicle market opportunity. However, that opportunity is complicated by the proliferation of engine and car companies. A universal GFI system has been proposed and is under development to dramatically reduce, if not eliminate, that complication. The GFI system appears to be capable of a "coarse" calibration level that will fuel the engine to within 10%, which the installer can further fine tune to within 2%, and which has a non-volatile adaptive memory which will further refine the metering for the life of the car.

This system is initially being developed for NGV-powered gasoline type engines. However, the system is applicable to, and funding is being sought for, propane (LPG) applications, and for application of the system to diesel-type engines operated as OTTO cycle engines.

The remaining technological hurdle that we see facing the ATF industry is implementation of a DIP protocol by the vehicle OEM's so that the car's gasoline computers will tolerate operation on ATF's. Pointedly, the need for a DIP protocol is independent of system concept (conventional gaseous carburetion systems or GFI) and fuel (NGV or LPG).

A Long Term Test of Ford Flexible Fuel Vehicles

June 21, 1988

R. L. Bechtold
EA-Mueller, Inc.
1401 South Edgewood Street
Baltimore, Maryland 21227

Project Participants

Sponsors: New York State Energy Research and Development Authority, in conjunction with New York State Thruway Authority

Ford: Flexible Fuel Systems, Vehicle Modification and Technical Assistance

Lubrizol: Lubricating Oil and Analysis Services

New York State Automotive Emissions Laboratory: Driveability and Emissions Testing

EA—Mueller Inc.: Technical Support Services

Project Objectives

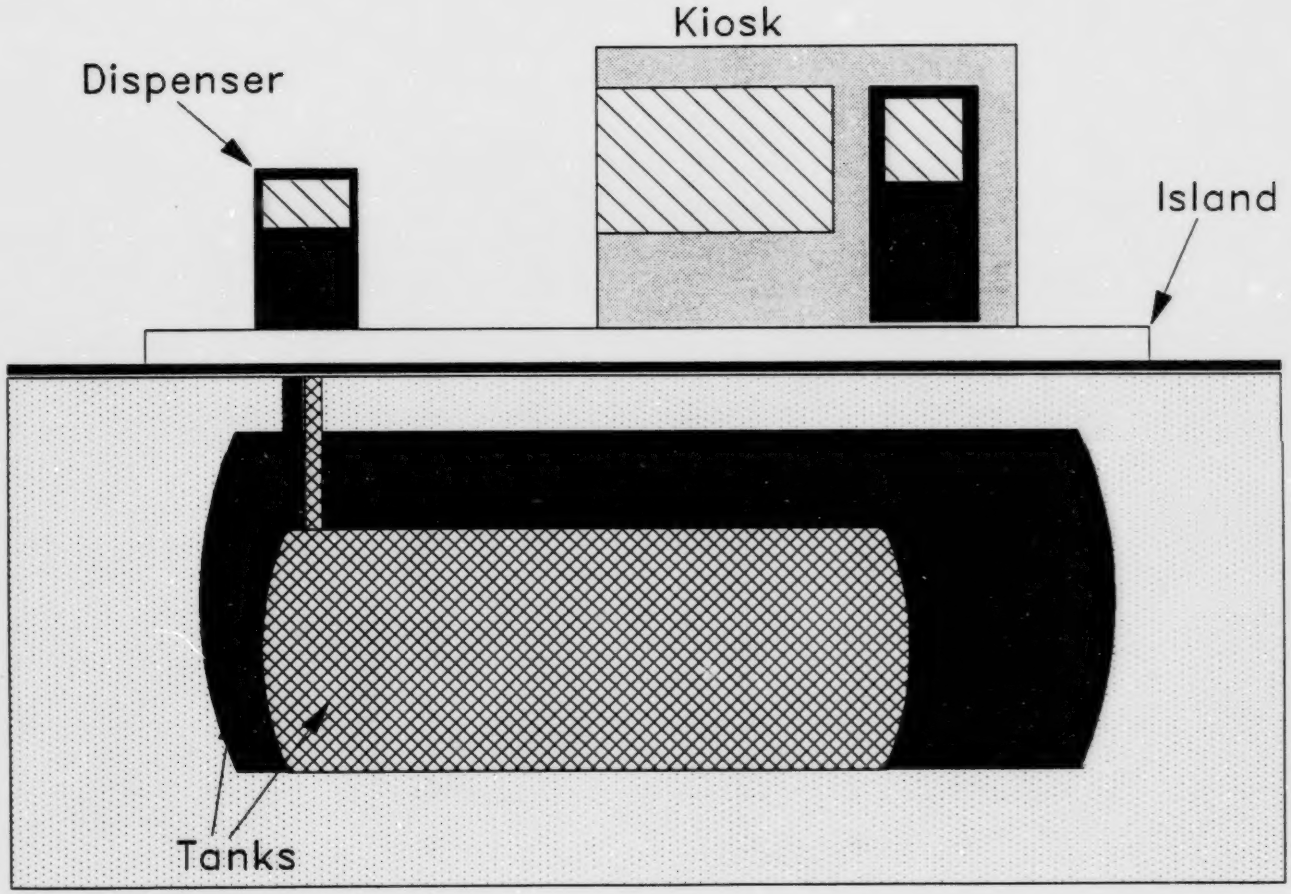
- Overall Goal: To Create Conditions Under Which the Methanol Supply Infrastructure and End-Use Applications can Develop in Concert.
- Evaluate the Operating Characteristics of Flexible Fuel Vehicles in a Northern Climate Using M85 Fuel.
- Measure Emissions and Emissions Deterioration for M85 Relative to Gasoline.
- Evaluate Two Engine Oils Formulated Especially for Flexible Fuel Vehicles.

Data Collection Plan

- Operate All Vehicles for 100,000 to 150,000 Miles (18 Months)
- Operate Two Vehicles on Gasoline for 30,000 Miles; Switch to M85
- Operate Two Vehicles Exclusively on M85
- Federal Test Procedure Emissions Including Aldehydes
- Catalyst Deterioration at Selected Points

Refueling Facility

- Blending Dispenser
- Methanol (10,000 gal) and Gasoline (2000 gal) Underground Tanks
- Capability to Supply Numerous Blends: M85, M50, M25 and M0
- Meets All Current NYS and EPA Regulations


Kiosk
Dispenser
Island
Tanks

Results To Date

Mileage Accumulation:
Vehicle #50 – 13,000 miles
Vehicle #80 – 10,000 miles

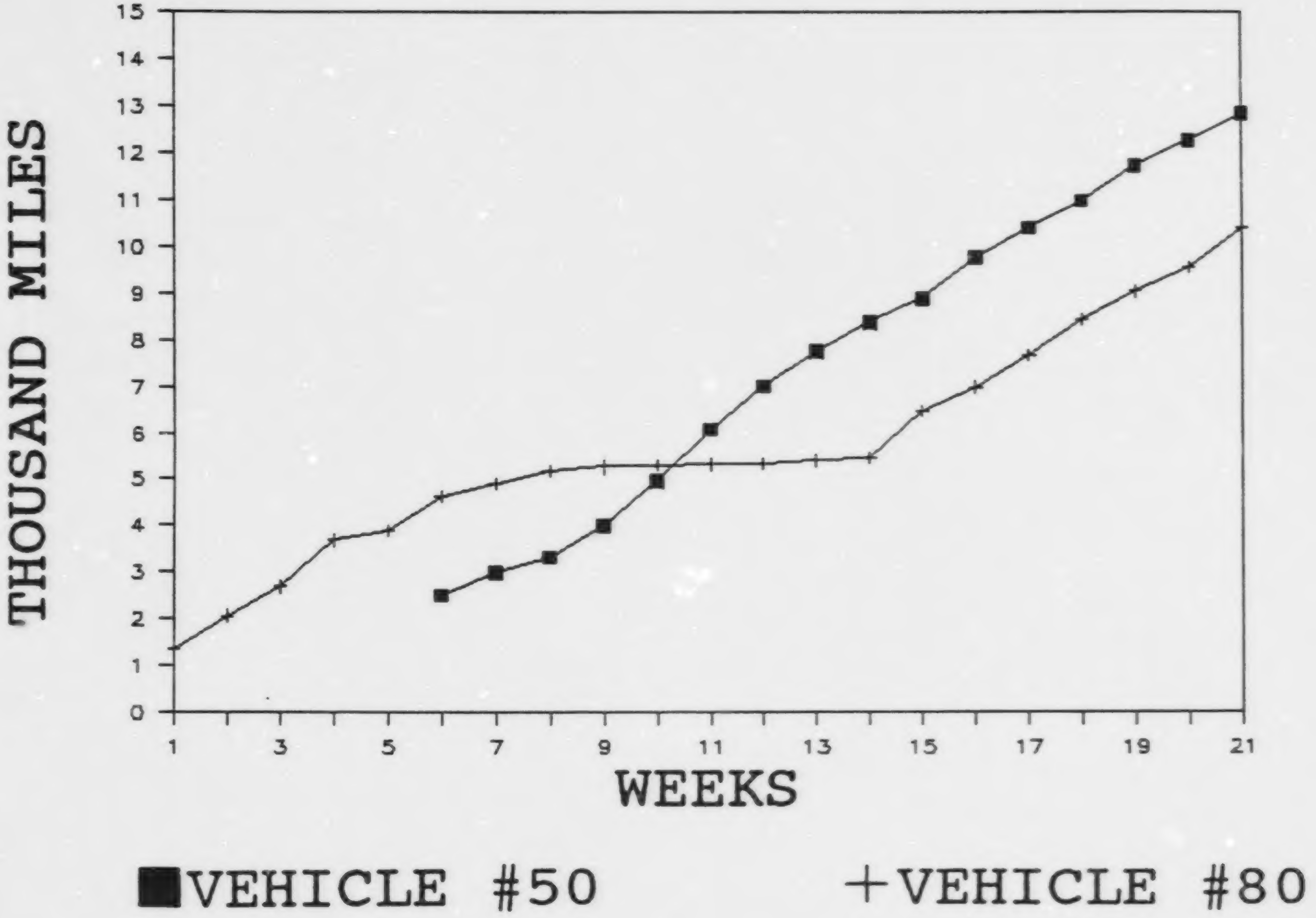
Driveability: Rated Excellent in Both Controlled Tests and by Drivers in the Field.

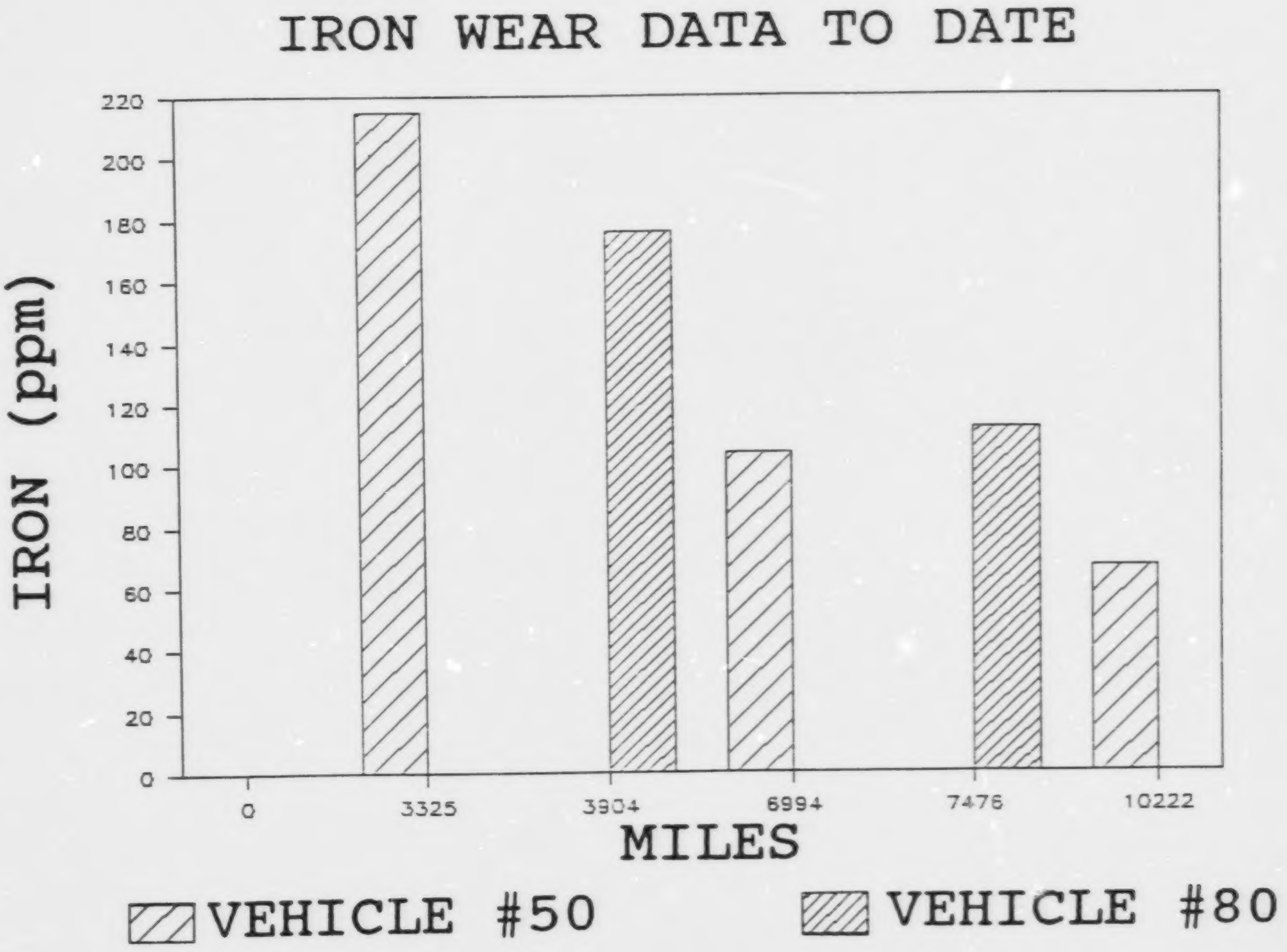
Emissions: Within Standards; Data Insufficient to Calculate Deterioration Rates.

FFV Component Durability To Date: Excellent

Oil Analyses: Both Oil Fomulations Appear to Work Equally Well Using Gasoline.

MILEAGE ACCUMULATION




IRON WEAR DATA TO DATE
IRON (ppm)
220
200
180
160
140
120
100
80
60
40
20
0
0
3325
3904
6994
7476
10222
MILES
▨ VEHICLE #50
▨ VEHICLE #80

Methanol Fuels: A Specification Dilemma

by

Charles E. Risch

Ford Motor Company

Presented at

Fourth Windsor Workshop on Alternative Fuels

June 21, 1988

PRIMARY CRITERIA FOR EVALUATION OF M100 VERSUS M85

- VEHICLE FUNCTION
- FLAME VISIBILITY
- IN-TANK FLAMMABILITY
- AIR QUALITY
- TOXICITY

COLD START CAPABILITY

Spark Ignited Light Duty Applications

50° F M100 IS DIFFICULT TO START AT TEMPERATURES BELOW 50° F

−20° F M85 DESIGN HAS DEMONSTRATED ACCEPTABLE STARTING AT −20° F

CONCERNS ASSOCIATED WITH A COLD START DESIGN UTILIZING A SECOND FUEL

- CUSTOMER ACCEPTANCE
- COST
- COMPLEXITY
- EMISSIONS
- SAFETY AND HEALTH

ADVANTAGES OF FLAME VISIBILITY

- EARLY WARNING OF FIRE
- WARNING TO AVOID THE FIRE
- AID IN EXTINGUISHING THE FIRE

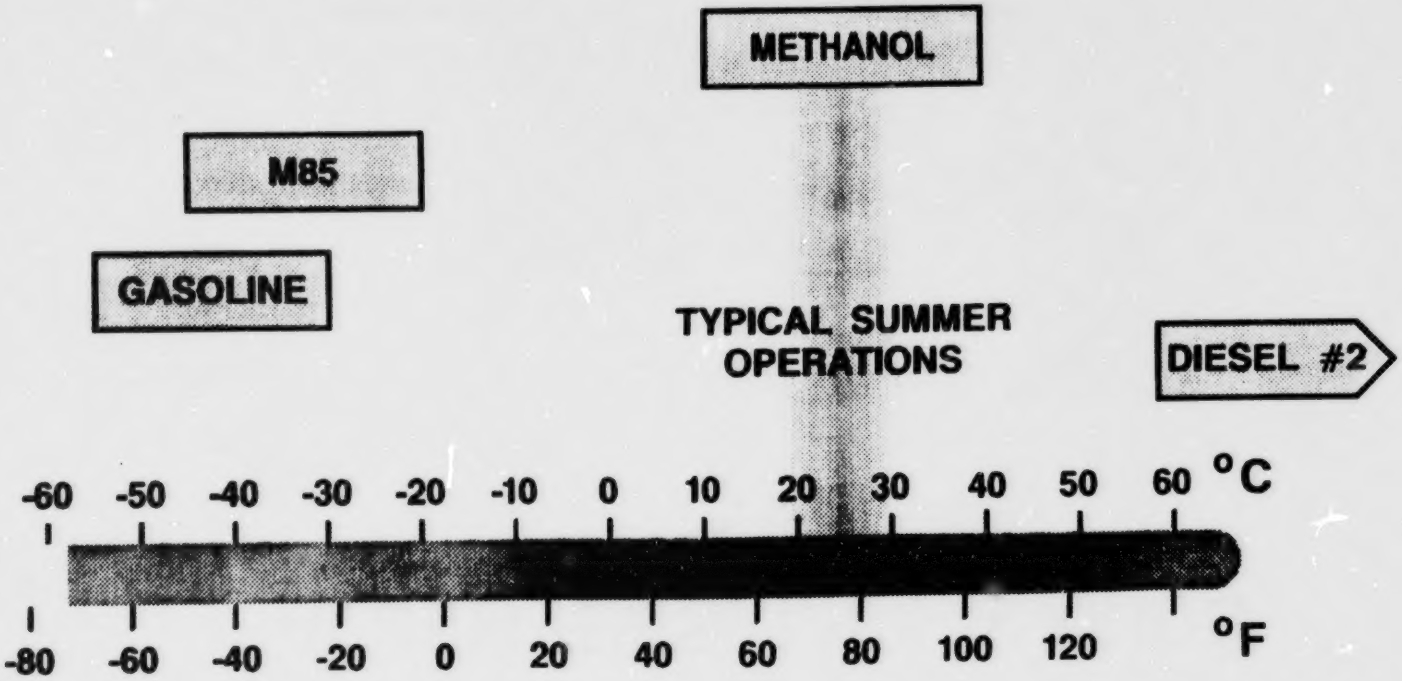
FLAME VISIBILITY

CONDITION	M100	M85
NIGHT	FAINT BLUE FLAME	VISIBLE FLAME
DAYLIGHT	INVISIBLE FLAME	VISIBLE FLAME

MAJOR POINTS OF RACING VIDEO

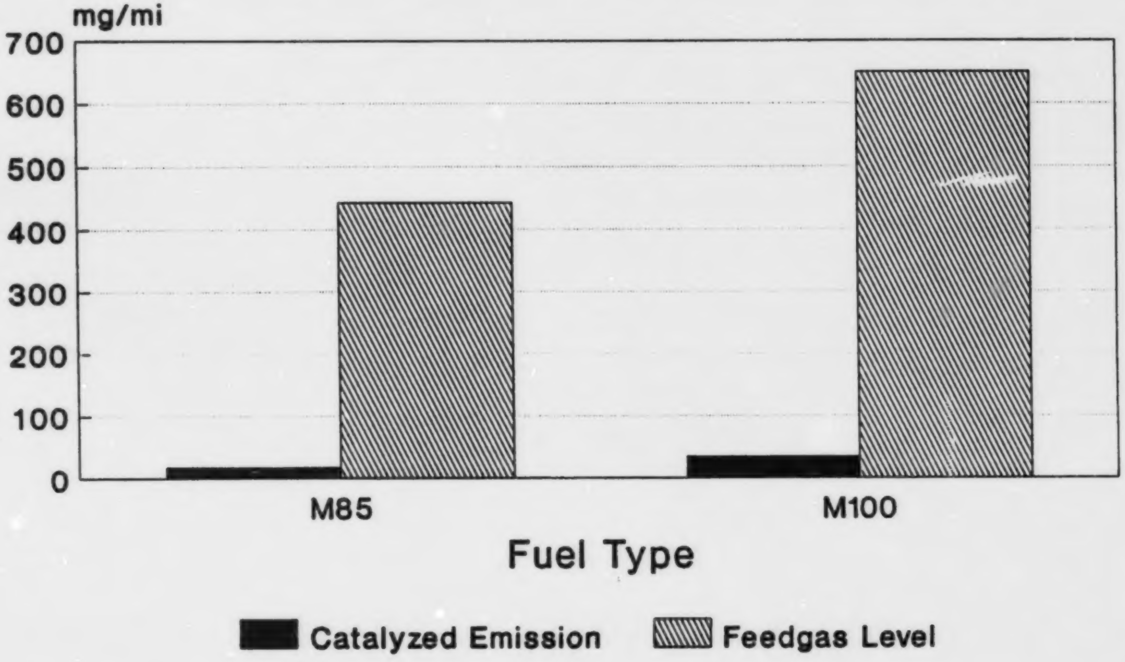
- M100 FIRE WAS NOT VISIBLE
- SECONDARY MATERIAL IN RACING ENVIRONMENT DID NOT ADD VISIBILITY
- FIRE FIGHTING DIFFICULTIES
- DISREGARD FOR LIQUID IN FIRE AREA
- PUBLIC PERCEPTION OF FIRE FIGHTING TECHNIQUES

VAPOR SPACE FLAMMABILITY
LIMITS OVER SUMMER GRADE LIQUID FUELS



ALDEHYDES, M85 & M100

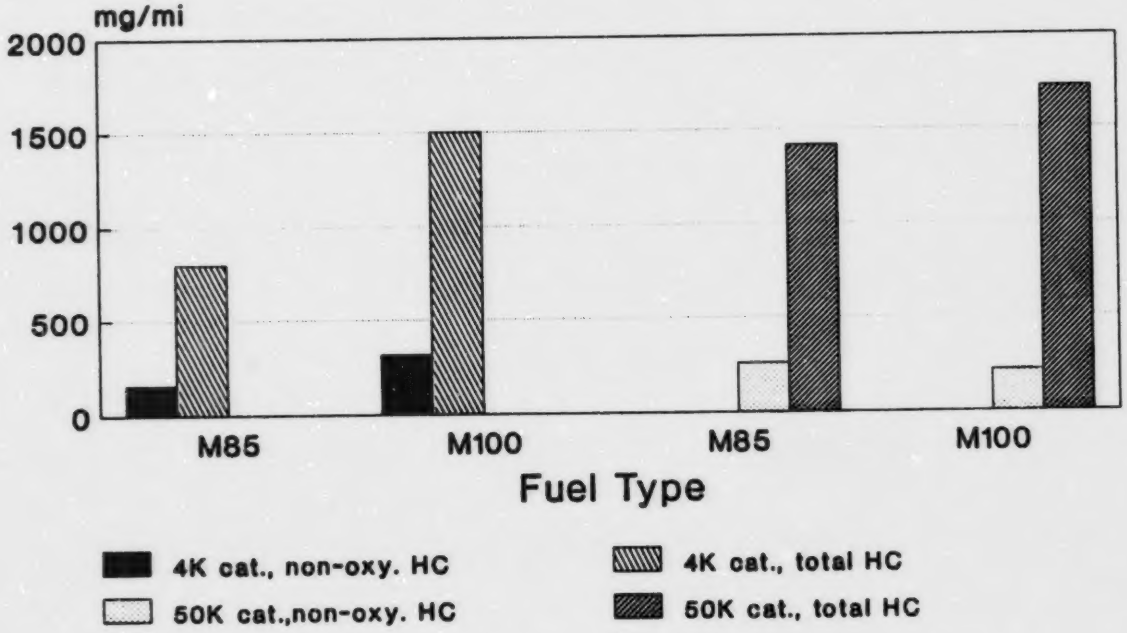
Feedgas & Catalyzed



DNPH Analysis, T520 with ~3K catalyst

HYDROCARBONS,M85 & M100

Non-oxygenated & Total HC



FTIR ANALYSIS, FFV Escort, prod. cat.

M85 VS. M100

- M85 may provide more air quality benefit.
- Aldehydes and unburned methanol are higher with M100.
- Tailpipe non-oxygenated HC are about the same for both fuels.
- Low ambient cold starts on M100 could negate methanol air quality advantage.
  - more rapid engine wear
  - cold start technique is unknown

TOXICITY

- EMPHASIS SHOULD BE ON PREVENTING CONSUMPTION
- M85 HAS GASOLINE TASTE AND ODOR WHICH IS A KNOWN DETERRENT
- M100 ADDITIVES TO DETER CONSUMPTION MUST BE COMPATIBLE WITH:
  - VEHICLE DESIGNS
  - ENVIRONMENTAL CONSIDERATIONS
  - CUSTOMER USAGES

M85 BENEFITS OVER M100

- ACCEPTABLE COLD START CAPABILITY
- FLAME VISIBILITY
- REDUCED IN-TANK FLAMMABILITY
- REDUCED ALDEHYDES WITH NO HC INCREASE
- TASTE AND ODOR THAT DETER CONSUMPTION

ALTERNATIVE FUELS _ A TECHNOLOGY OPPORTUNITY

R. Skinner
Energy, Mines and Resources

NO PAPER AVAILABLE

ENVIRONMENTAL PERSPECTIVES
ON
ALTERNATE FUELS

Presented At The Fourth Windsor Workshop
on Alternate Fuels
June 1988

ALTERNATE FUELS

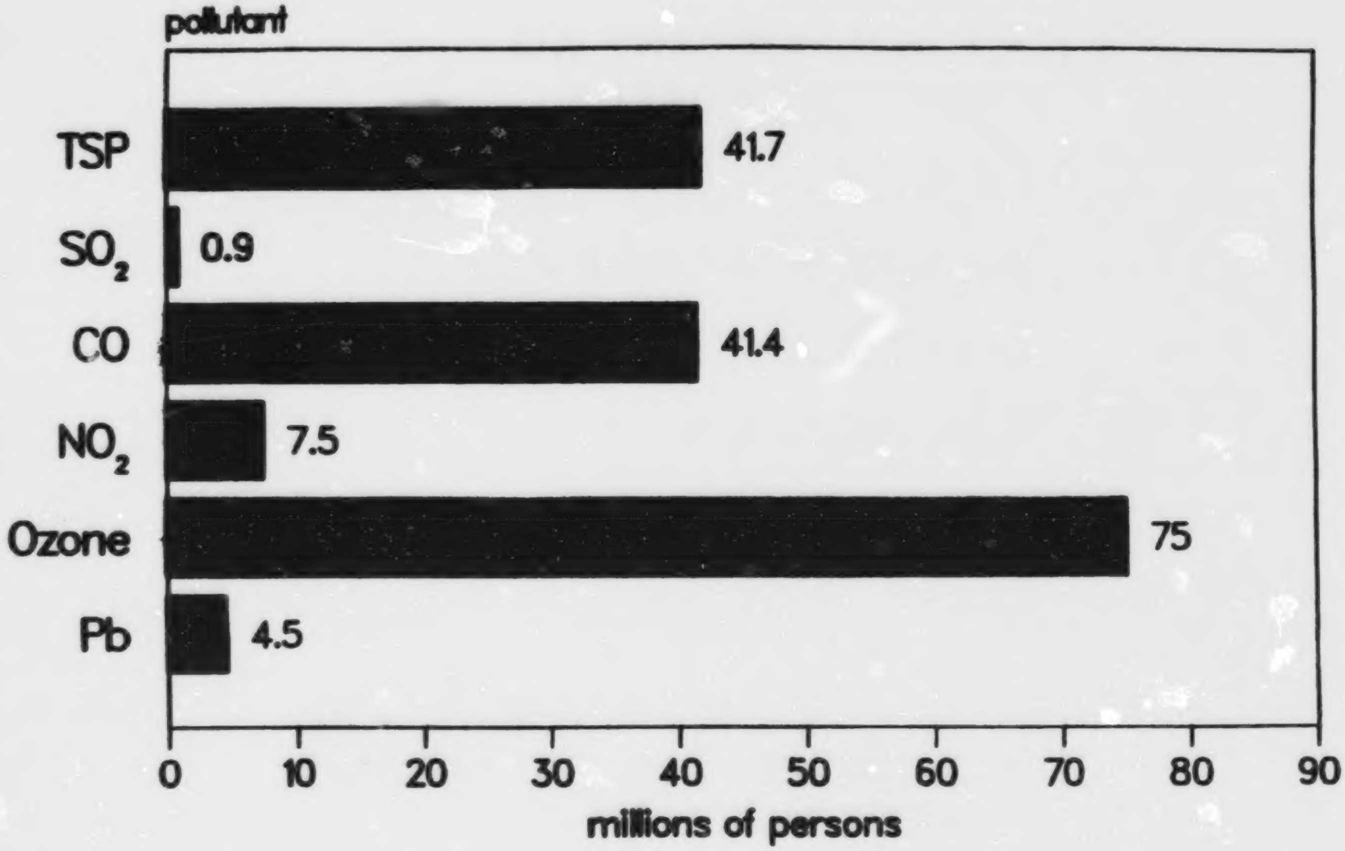
- WHAT ALTERNATE FUELS SHOULD BE CONSIDERED?
- WHAT ENVIRONMENTAL ASPECTS SHOULD BE DISCUSSED?
- WHAT DATA NEEDS EXIST?
- WHAT TECHNICAL DEVELOPMENTS ARE IMPORTANT?

Possible Alternatives To Petroleum for Transportation

- Oxygenated fuels
  - Alcohols
    - Ethanol ✓
    - Methanol ✓
  - Ethers
    - MTBE
- Gaseous Fuels
  - CNG ✓
  - LNG
  - LPG
- Electricity
  - Batteries ✓
  - Fuel cells

ENVIRONMENTAL CONSIDERATIONS

- NATIONAL AMBIENT AIR QUALITY STANDARDS
  - OZONE ✓
  - CARBON MONOXIDE ✓
  - PARTICULATES ✓
  - NITROGEN DIOXIDE
  - SULFUR DIOXIDE
  - LEAD
- OZONE, CARBON MONOXIDE, AND PARTICULATES ARE THE LARGEST CURRENT PROBLEMS



Number of Persons Living in Counties with Air Quality Levels Above the Primary National Ambient Air Quality Standards in 1986

(Based on 1980 population data)

TOPICS FOR DISCUSSION

- FUEL/ENERGY
  - ETHANOL
  - METHANOL
  - CNG
  - BATTERIES
- POLLUTANTS
  - HC
  - CO
  - PARTICULATES
- BLENDS VS. NEAT FUELS
  - ALCOHOLS
- MORE THAN ONE FUEL VS. ONE FUEL
  - DUAL FUEL
  - FFV/VFV

HC EMISSIONS ALCOHOLS

- ALCOHOLS, METHANOL AND ETHANOL
  - Blends: Fuel Vapor Pressure Effects Evaporative Emissions, Running Losses With Low Level Blends (+1 RVP For Gasohol?)
  - Neat Ethanol: Most Experience In Brazil With Different Emission Requirements, Methanol: Total HC Control Implies Aftertreatment
  - Aldehydes: Major Ozone Precursor Of Concern For Both Alcohols In Use
  - FFVs: In Use HC Emissions A Function Of Fuel Actually Used
  - Evap, Running Loss, Refueling Controls With Blends May Be More Difficult Than With Neat Fuels Or Gasoline

HC EMISSIONS
CNG

- CNG
  - Total HC Emissions Usually High Both Dedicated and Dual Fuel
  - Fuel and Emissions Mostly Methane Methane Considered Photochemicall Unreactive
  - With Catalytic Aftertreatment Nonmethane HC Can Be Low
  - Aldehyde Emissions Same Order of Magnitude As Gasoline-Fueled Cars

HC EMISSIONS
BATTERIES

- BATTERIES
  - HC From Two Sources:
    Electricity Generation
    On Board Auxillary Power (APU)
  - Powerplant Emissions
    Depend On Fuel/Control Used
    Probably Low
  - Auxillary Engines Need Very
    Efficient Emission Control
    Systems To Be As Good As
    Today's Cars

CO EMISSIONS

- ALCOHOLS
  - Can Be Controlled To Low Levels
  - Control Details For CO Depend On Method Used To Control NOx
  - FFVs: Operation at Stoich. With Gasoline Needed
  - Blends A Local CO Strategy Option
- CNG
  - Dedicated Vehicles Can Be Very Low In CO
    No Or Little Fuel Enrichment
    Needed to Start
  - Dual Fuel CO Levels Sensitive To Adjustment
    Can Be Variable
- BATTERIES
  - Powerplants Not Much Concern
  - APU Reductions Needed

PARTICULATE EMISSIONS

- ALCOHOLS AND CNG
  - As S.I. Fuels Not Much Of A Concern
  - As C.I. Fuels Replaceing Diesel Fuel Can Be A Benefit
  - Methanol Better Than Ethanol In Some Engines

- BATTERIES
  - Depends On The Fuel Source And Controls For The Generation
  - APUs Not Much Concern If Non-Diesel

DATA NEEDS

- ETHANOL
  - Effect Of Blends On Volatility Related Emissions, Evap Refueling and Running Losses During High Ambient Temperature Operations
- METHANOL
  - High Mileage, In Use Emission Data On Advanced M100 Prototype Vehicles, Especially Data On Aldehydes
  - Sensor Durability Data For FFVs
- CNG
  - Current Dual Fuel In Use Emissions On Both Gasoline And CNG
  - VOC Makeup Of Exhaust From Catalyst-Equipped Vehicles
- BATTERIES
  - Operational/System Evaluation To Project Need For APU

IMPORTANT TECHNICAL DEVELOPMENTS NEEDED

- ALCOHOLS
  - Development Of Low Aldehyde Emission Control Systems
  - Exploring The Limits Of Lean Versus Stoich Operation With Neat Fuels As A Function Of NOx Level (Standard) Needed
  - Improved Cold Starting Approaches With Neat Fuels
  - Dissociation System For Methanol
- CNG
  - Development Of Feedback Controllable Fuel Metering Systems--A/F Ratio Sensor Can Work Both Lean And At Stoich
- BATTERIES
  - Eliminate APUs or Make Them Very Clean

ENVIRONMENTAL AND ENERGY ANALYSIS OF ALTERNATIVE FUELS

An Overview of the U.S. Department of Energy Flexible Fuel Study

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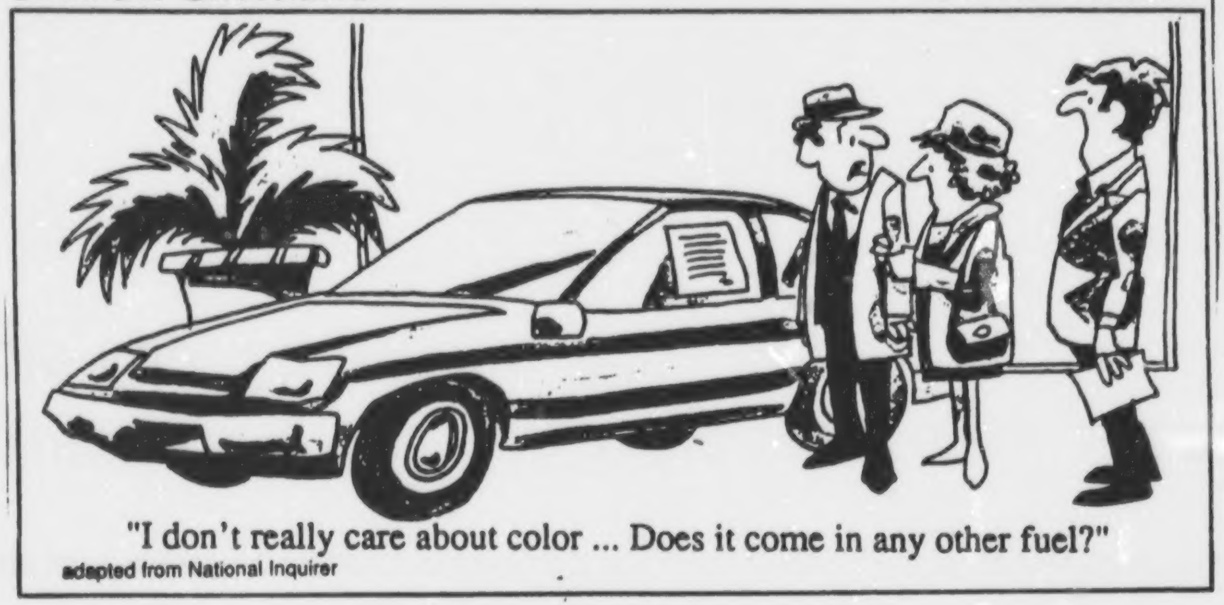
BUMPER SNICKERS

BY BILL HOEST



"I don't really care about color ... Does it come in any other fuel?"

adapted from National Inquirer

ORIGIN OF THE STUDY: ENERGY SECURITY A REPORT TO THE PRESIDENT

- Even efficient vehicles will leave the U.S. dependent on imported oil
- Alternative fuels are the most promising option
- Alternative fuels complement efficiency improvements
- Therefore, DOE will conduct a technical analysis of the benefits and costs of a flexible fuel transportation system

NECESSITY FOR A FLEXIBLE AND ALTERNATIVE FUELS STUDY

- Timing: alternative fuels moving from technology development to market development
- The need to put alternative fuels potential on an analytical par with other energy security options, such as:
  - enhanced oil recovery
  - additional oil exploration
  - higher CAFE standards
- No fuel substitute in transportation
- Transportation's share of oil consumption continues to increase
- Energy vulnerability is increasing as oil imports grow

LEADING CANDIDATES FOR FLEXIBLE-FUELED VEHICLES

Alcohol Fuels

- Vehicle flexible in using variable amounts of gasoline or alcohol

Gaseous Fuels

- Dual-fueled vehicles using gasoline or CNG/LPG

Electric Vehicles

- Fuel alternatives at the powerplant

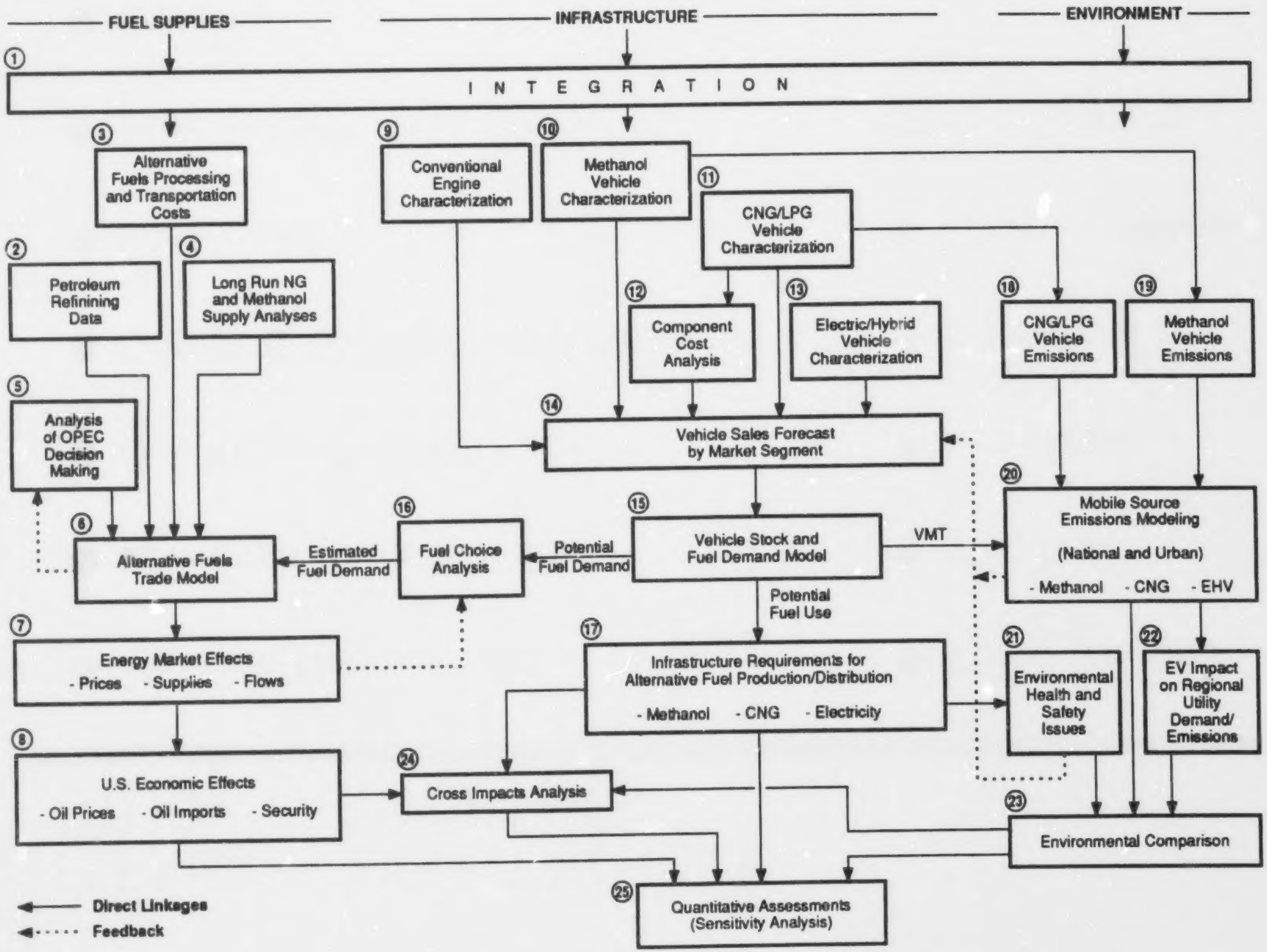
ISSUES TO BE ADDRESSED IN THE FLEXIBLE FUEL STUDY

- Fuel supplies: source, volume, and cost
  - effect of alternative fuels on world oil and gas markets
  - effect on OPEC oil market control
  - relative security

- Vehicle/fuel infrastructure requirements
  - vehicle technology characterization and market forecast
  - fuel production and distribution needs
  - potential alternative fuel demand

- Relative environmental impacts
  - emissions
  - health and safety impacts

U.S. DOE FLEXIBLE AND ALTERNATIVE FUEL VEHICLE STUDY


FUEL SUPPLIES
INFRASTRUCTURE
ENVIRONMENT
①
INTEGRATION
③ Alternative Fuels Processing and Transportation Costs
⑨ Conventional Engine Characterization
⑩ Methanol Vehicle Characterization
⑪ CNG/LPG Vehicle Characterization
② Petroleum Refinining Data
④ Long Run NG and Methanol Supply Analyses
⑫ Component Cost Analysis
⑬ Electric/Hybrid Vehicle Characterization
⑱ CNG/LPG Vehicle Emissions
⑲ Methanol Vehicle Emissions
⑤ Analysis of OPEC Decision Making
⑭ Vehicle Sales Forecast by Market Segment
⑳ Mobile Source Emissions Modeling (National and Urban) - Methanol - CNG - EHV
⑥ Alternative Fuels Trade Model
Estimated Fuel Demand
⑯ Fuel Choice Analysis
Potential Fuel Demand
⑮ Vehicle Stock and Fuel Demand Model
VMT
Potential Fuel Use
⑦ Energy Market Effects - Prices - Supplies - Flows
⑰ Infrastructure Requirements for Alternative Fuel Production/Distribution - Methanol - CNG - Electricity
㉑ Environmental Health and Safety Issues
㉒ EV Impact on Regional Utility Demand/ Emissions
⑧ U.S. Economic Effects - Oil Prices - Oil Imports - Security
㉔ Cross Impacts Analysis
㉓ Environmental Comparison
㉕ Quantitative Assessments (Sensitivity Analysis)
Direct Linkages
Feedback

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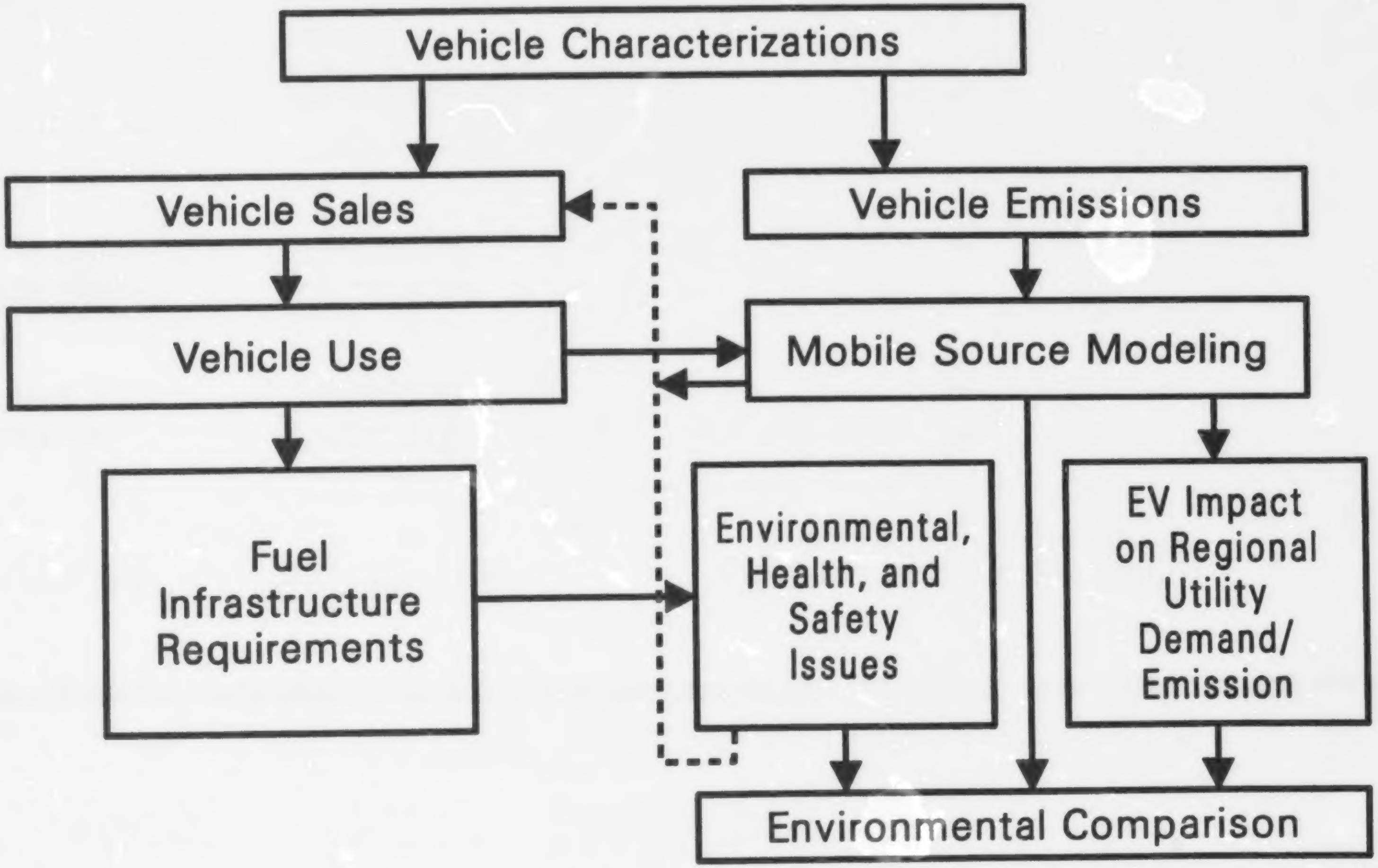
ENVIRONMENTAL ANALYSIS OF FLEXIBLE-FUELED VEHICLES



Vehicle Characterizations

Vehicle Sales

Vehicle Emissions

Vehicle Use

Mobile Source Modeling

Fuel Infrastructure Requirements

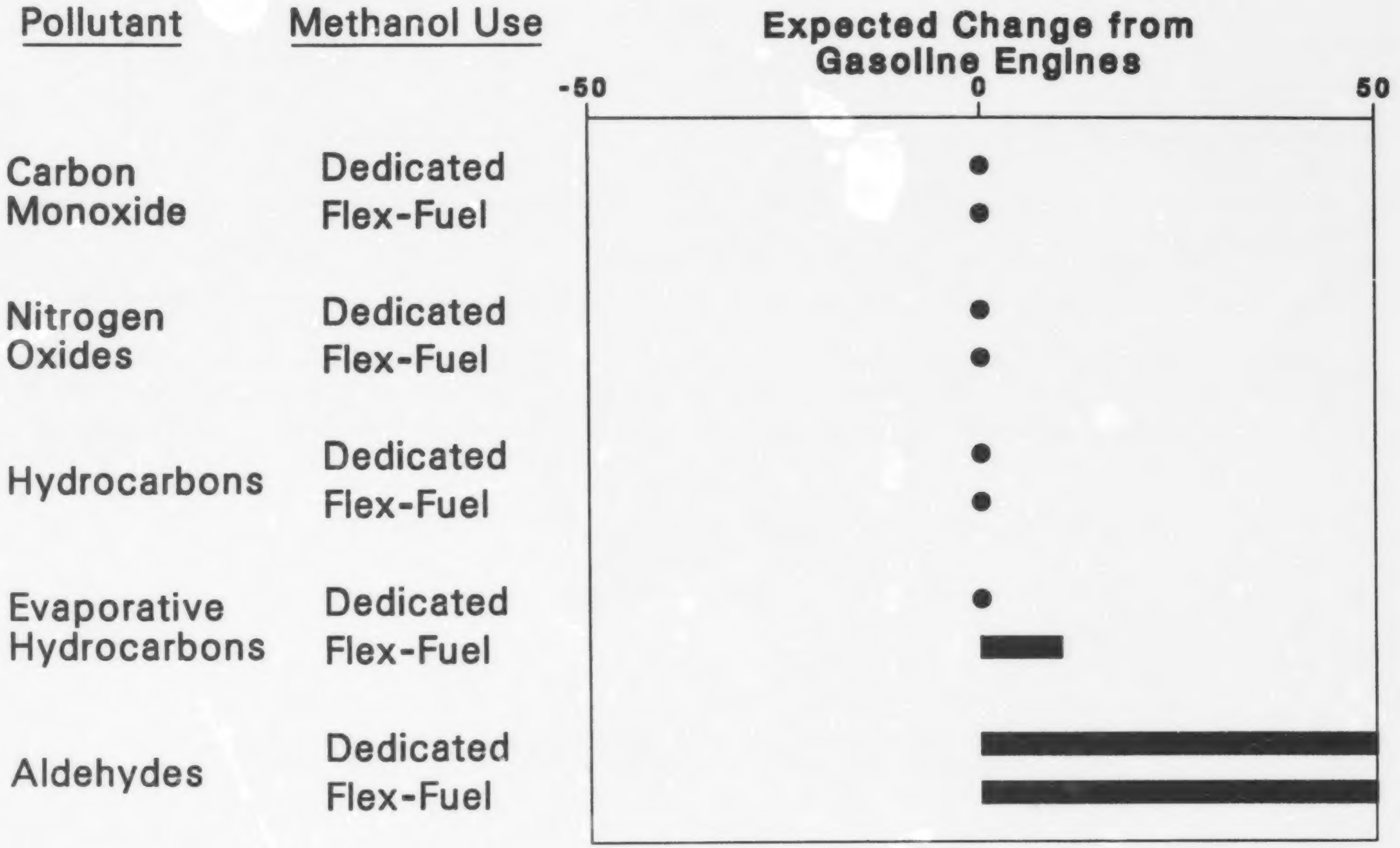
Environmental, Health, and Safety Issues

EV Impact on Regional Utility Demand/ Emission

Environmental Comparison

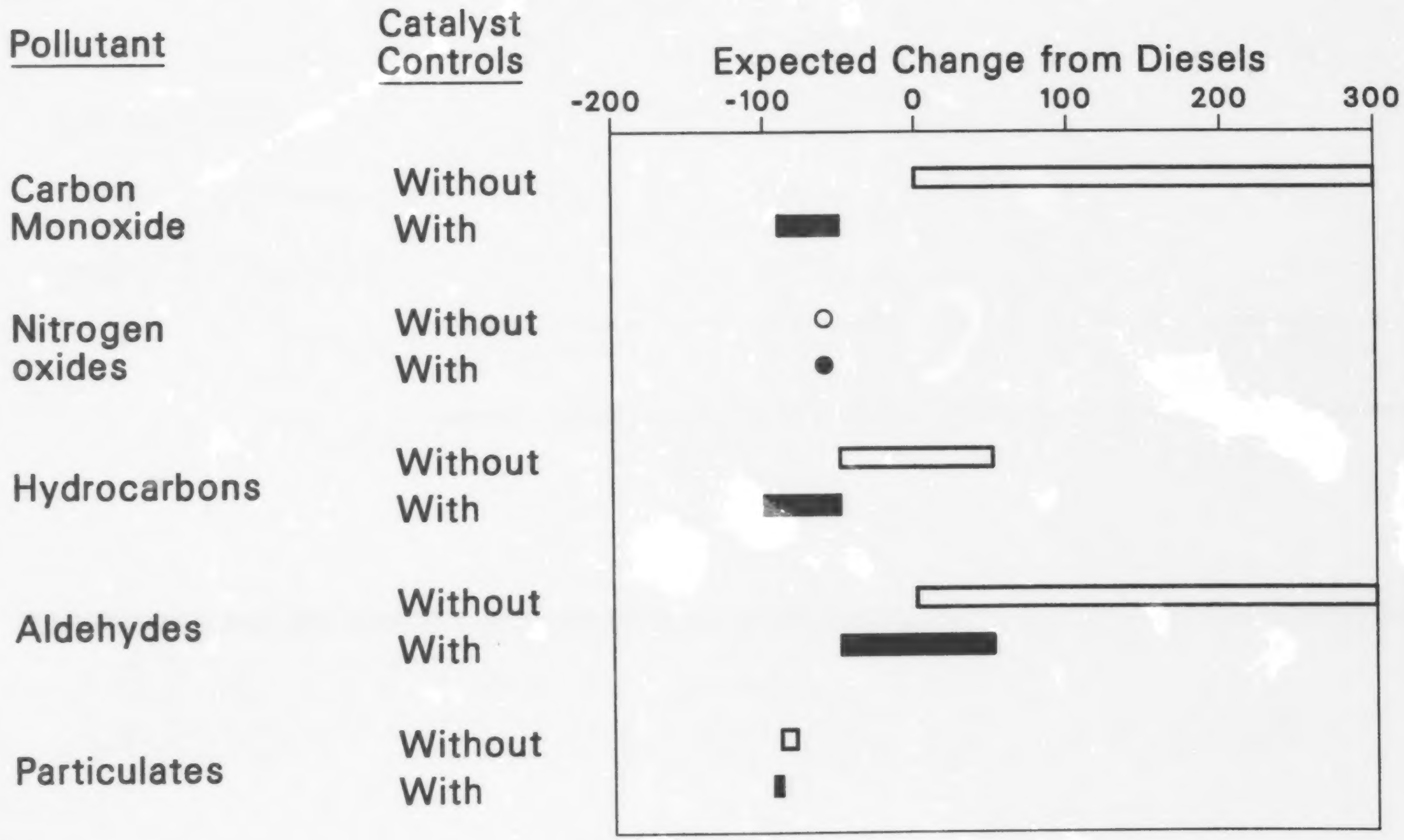
METHANOL VEHICLE EMISSIONS

Light Duty, Spark-Ignition, Fuel-Injected, Passenger Car



METHANOL VEHICLE EMISSIONS

Glow Plug, Surface Ignition, Heavy Duty Diesel Truck (Pre-1985)



EMISSIONS FROM METHANOL PRODUCTION AND PETROLEUM REFINING

	Tons/yr		Tons/yr/10^{12} Btu	
	Methanol	Petroleum	Methanol	Petroleum
Nitrogen Oxides	1860	7700	108.2	19.5
Carbon Monoxide	40	N/A	2.3	N/A
Particulates	Nil	2200	Nil	5.1
Hydrocarbons	Nil	5000	Nil	11.5
Methanol	5	None	0.3	None
Sulphur Oxides	2	6050	0.1	13.9
Carbon Dioxide	283,000	N/A	16,500	N/A

METHANOL EFFECTS ON PHOTOCHEMICAL SMOG

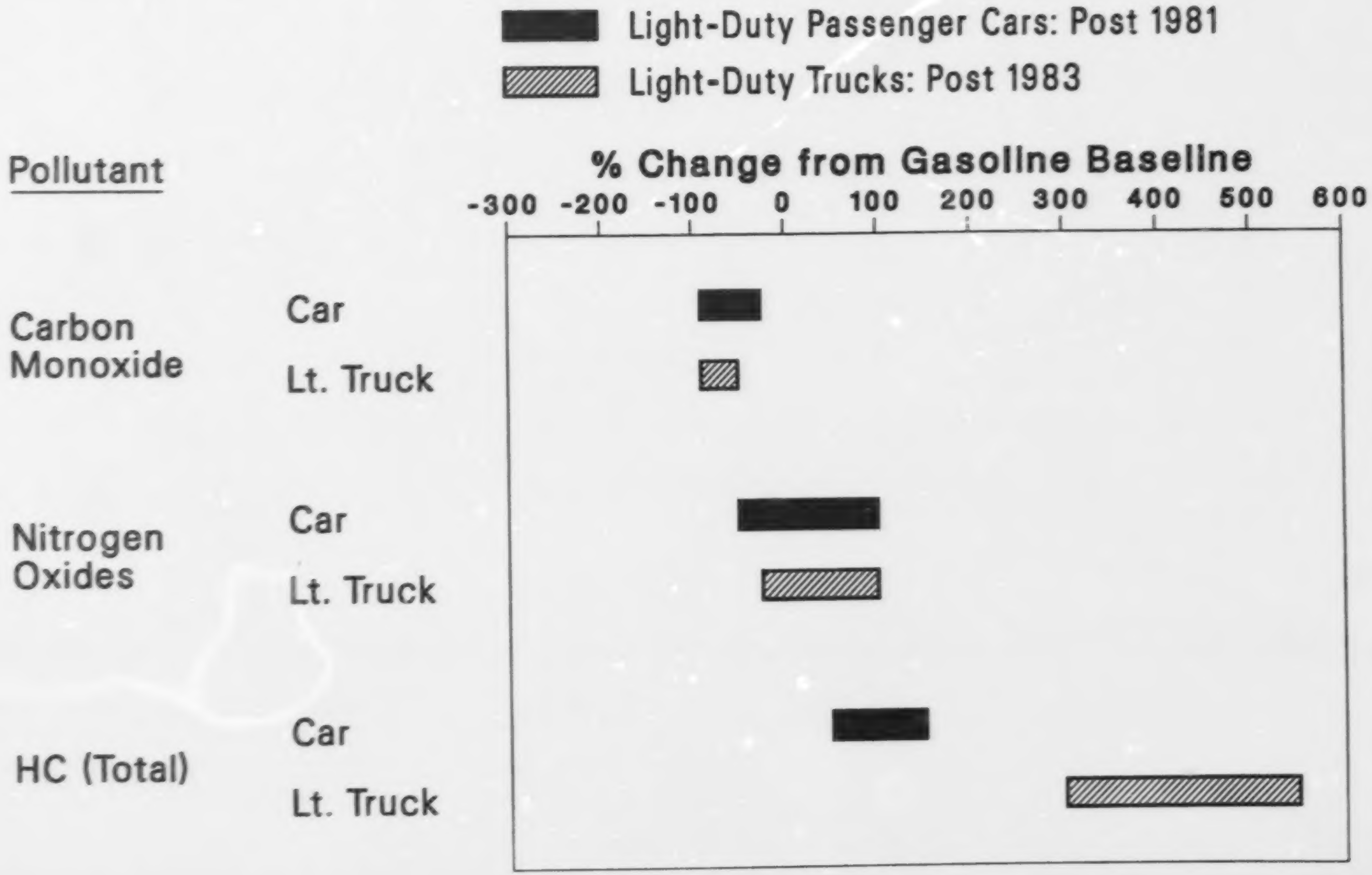
- Smog - largely caused by interactions of NO_x, HC, and SO_2
- Methanol vehicle emissions versus gasoline vehicles
  - may reduce NO_x, but depends on dedicated or flex fuel configuration
  - methanol not a contributor to SO_2
- Reduced photochemically-active hydrocarbons
  - unburned methanol 2 to 43% as reactive as non-methane HC
  - multi-day reactivity may increase
- Formaldehyde emissions must be considered
  - uncontrolled emissions greater for methanol
  - controlled emissions may be equal or less

EFFECTS ON REGIONAL EMISSIONS OF NEAT METHANOL USE

- Modest changes in the major transportation pollutants
  - negligible change in CO
  - 1-3% reduction in NO_x
  - 1-6% reduction in HC

- Goal of the present flex-fuel study
  - model emission on subregional level
  - highlight localized contributions

EXPECTED EMISSIONS CHANGE WITH NATURAL GAS VEHICLES



TECHNOLOGY CONSIDERATIONS FOR NATURAL GAS VEHICLES

- Advances in catalytic converter design necessary to meet gasoline hydrocarbon standard
- Natural gas converion systems generally not compatible with electronic feedback systems on current vehicles
- LNG has same combustion emission characteristics as CNG, but increased methane emissions due to LNG boil off from cryogenic storage tank

AIR QUALITY EFFECTS OF NATURAL GAS VEHICLES

- Methane contribution to global warming, but 80% of atmospheric methane is of biological origin
- Potentially significant CO_2 release from extraction, purification, and combustion
- Potential ozone formation reduction of 50-90%
- Potentially effective element in strategies for CO and ozone non-attainment areas

ENVIRONMENTAL EFFECTS OF ELECTRIC VEHICLES

- Including power plant emissions, EVs (on a per-vehicle basis) would provide
  - significant reduction in CO and HC emissions
  - some reduction in NO_x and PM emissions
  - significant increase in SO_x
- High incremental water pollution possible in vicinity of materials and fuels extraction, processing, and manufacturing
- Land requirements for solid waste disposal much larger for EVs than for CVs
- Limited effect on noise pollution

POTENTIAL URBAN AIR QUALITY IMPACTS OF ELECTRIC VEHICLES

- Older studies indicated modest benefits - up to 5 % reduction in emissions
- Recent Los Angeles study indicates major benefits possible - especially CO and ozone

PRELIMINARY ENVIRONMENTAL CONCLUSIONS

- With appropriated controls, vehicles using methanol, CNG, or electric power should be no worse (and in many instances better) than conventional vehicles

- The environmental modeling and analysis in the DOE study should:
  - identify localized benefits or potential problems
  - provide improved quantification of the regional emissions changes

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